Summer 7-27-2011

TRANSPIRATION-USE EFFICIENCY COEFFICIENT OF SEVEN WEED SPECIES AS AFFECTED BY FRACTION OF TRANSPIRABLE SOIL WATER AND GROWTH STAGE

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by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Agronomy

Under the Supervision of Professor Mark L. Bernards

Lincoln, Nebraska

August, 2011

Transpiration-use Efficiency Coefficient of Seven Weed Species as Affected by Fraction of Transpirable Soil Water and Growth Stage

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University of Nebraska, 2011

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Transpiration-use efficiency coefficient (K_c) describes the amount of biomass produced per unit transpiration at a given vapor pressure deficit. A series of greenhouse experiments were conducted to determine the K_c values of seven weed species and to measure how K_c values were affected by fraction of transpirable soil water (FTSW) level and plant growth stage. Experiments were conducted using a factorial design with 4 levels of water stress (0.3, 0.4, 0.7, and 1.0 FTSW) and two harvest times (first bloom and seed maturity). After plants attained a predetermined size, each plant was sealed at the base using a polyethylene bag. Pots were weighed daily and maintained the required weight by watering through an inserted syringe. Pre-bagging transpiration was back-calculated from 0 d to the first 20 d of measured daily transpiration. One set of plants was harvested at first bloom and another set was harvested at seed maturity. K_c was calculated as the ratio of total biomass to the cumulative transpiration multiplied by the average daytime vapor pressure deficit.

FTSW level did not affect the K_c of henbit (vegetative growth) or shepherd's-purse. K_c values increased as FTSW levels declined for common lambsquarters, pinnate tansymustard, henbit (complete lifecycle) and field pennycress (vegetative growth). K_c values decreased as FTSW declined for dandelion, Carolina foxtail, and field pennycress

(complete lifecycle) suggesting that these species were relatively sensitive to water stress. Plant growth stage did not affect K_c for pinnate tansymustard and dandelion. K_c values decreased between the first bloom and seed maturity for field pennycress, common lambsquarters, shepherd's-purse and henbit. The decline in K_c may be attributed to high oil content in the seed of field pennycress, shepherd's-purse and henbit, and the high protein content of common lambsquarters. Carolina foxtail K_c values did not respond consistently to FTSW across harvest times – K_c values increased from first bloom to seed maturity at FTSW levels 0.3 and 0.4, but remained same at the 0.7 FTSW level.

ACKNOWLEDGEMENTS

I would like to thank my mentor Dr. Mark Bernards for his patience, enthusiasm, guidance, assistance and encouragement throughout the course of my stay at the graduate school. The opportunity to work on this project along with his guidance throughout is very much appreciated.

I would also like to thank Dr. John Lindquist, Dr. Tim Arkebauer, Dr. Stevan Knezevic and Dr. Suat Irmak for their invaluable insight and support on the findings of this research. The statistical analysis of this work would not have been possible without the assistance of Drs. Erin Blankenship; to whom, I am truly indebted.

I would also like extend my gratitude to student helpers, and research technician who not only toiled with me in the greenhouse, but whom also I have come to think of as close friends. In particular, I want to thank Kevin Horky, Rodrigo Werle, Leandro Manzano, and Lucas Perim.

I would also like to extend my gratitude to the fellow graduate students, whose advise, discussion and friendliness made these past four years an enjoyable experience. In particular, I want to thank Eric Frasure, Logan Vaughn, K.N., S.G., D.J., Lilyrani Sahoo, Jared Schmidt, Nabaraj Banjara, Kundan Dhakal, Santiago Ulloa, Sam Wortman, Roberto Javier Crespo, and Ryan Rapp.

Finally, I want to thank my parents, Ramaiah and Seshamma, and my friends back home who have stayed close despite me being far away. Most of all, I want to thank my beautiful wife, Swapna, to whom I am a greatest admirer. No one has put as much into this endeavor as she, always placing my needs in front of hers. She has always been willing to advise, guide, console, encourage and love.

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INTRODUCTION

No-till agricultural systems have been adopted widely (Klassen 1991; Swanton and Weise 1991; Swanton et al. 1993) to reduce labor and fuel inputs (Brown et al. 1989; Griffith et al. 1986; Hairston et al. 1984) and to minimize the level of interference to the environment (Hildebrand 1990; Reganold et al. 1990). No-tillage practices are beneficial to the farmer in terms of reduced soil erosion, improved water infiltration, improved surface water quality, greater soil moisture retention, better soil tilth, and reduced soil compaction (Griffith et al. 1986; Hairston et al. 1984). Long-term use of no-tillage leads to altered weed species composition, weed density, weed emergence patterns (Buhler 1995; Doll et al. 1992; Wicks et al. 1994), and greater reliance on herbicides to manage weeds (Buhler 1988; Coffman and Frank 1991; Koskinen and McWhorter 1986; Nowak 1983).

Weeds compete with crops for water, nutrients, light, and may also act as alternate hosts for plant diseases or insect pests (Creech et al. 2007; Johnson et al. 2004). Between 1996 and 2006, the percentage of corn acres in no-till increased from 17 to 74% in areas of southeast Nebraska (Franti et al. 2009). With that change there are an increasing number of fields infested with high densities of henbit, field pennycress, shepherd's-purse, pinnate tansymustard, marestail and other winter annual weeds. On some of the infested acres farmers delay controlling these weeds until the time of corn or soybean planting, and in extreme cases may even wait until after the crop has been planted and emerged. When winter annual weed control was delayed until planting or later, crop emergence and growth was reduced, especially in drier than normal springs (A. Martin, personal communication). Weed competition does not always affect soil water availability, but can have severe effects on crop growth and yield during extended dry periods (Dalley et al. 2004, 2006). There is little data on the effect of winter annual weeds on the growth and development of the subsequent crop, nor is there data on the water use of winter annual weeds.

The ratio of total biomass to the cumulative transpiration is the simplest definition of transpiration use efficiency (TUE) (Sinclair et al. 1984). Early work on water use efficiency of several crop and weed plants was done by Briggs and Shantz (1914), Dillman (1931), and Shantz et al. (1927). Briggs and Shantz (1914) measured water use efficiency of various cultivars of corn, wheat, oats, sorghum, 15 species of legumes, and grasses, forbs and shrubs by growing plants in 15 kg of sealed earthen pots. Water use efficiency of corn and sorghum cultivars ranged from 220 to 400 kg H_2O per kg dry matter and from 571 to 935 kg H_2O per kg dry matter for 14 legume species. Shantz et al. (1927) and Dillman (1931) conducted pot experiments to determine the water use efficiency and transpiration coefficients of several crop and weed species. They have also determined the amount of water required to produce one pound of dry matter.

The definition described above and the concept used by Briggs and Shantz (1914) does not account for differences in environmental conditions which might be responsible for differences in transpiration use efficiency of a particular plant species across environments. Consequently, a 'vapor pressure deficit' term was introduced into the definition, and the transpiration-use efficiency coefficient (K_c) described the amount of biomass produced per unit amount of water transpired at a given vapor pressure deficit (Sinclair et al. 1984; Kemanian et al. 2005) and is calculated using the equation (1):

$$K_c = \left[\frac{Y}{T}\right](e_a^* - e) \quad (1)$$

where K_c = transpiration-use efficiency coefficient (Pa), Y = crop above-ground biomass production (kg ha^{-1}), T = total canopy transpiration per area during growth to harvest (kg ha^{-1}), $e*_a$ = saturation vapor pressure at air temperature (Pa), and e = actual vapor pressure (Pa).

K_c values are preferred over transpiration use efficiency values because the vapor pressure deficit term help minimizing the variation in K_c values across environments. K_c values have been reported for many crop species (Table 1) but not for weed species. Knowing the K_c for a species allows one to calculate the amount of water used by that species at a given biomass and it may also help explain the relative competitiveness of a crop and a weed in water-sufficient or water-stressed environments. For example, if the K_c of a weed species is relatively greater than crop species it may be more competitive under water-deficit conditions.

The leaf level transpiration-use efficiency coefficient (K_l) was defined by Sinclair et al. (1984) and is calculated using equation (2):

$$K_l = \left[\frac{A}{E}\right] D_1 \quad (2)$$

where K_l = leaf level transpiration-use efficiency coefficient (Pa), A = CO_2 assimilation rate per unit of leaf area (µmol m^{-2} s^{-1}), E = rate of evaporation per unit leaf area (µmol m^{-2} s^{-1}), and D_l = leaf-to-air vapor pressure deficit (Pa).

Assuming the leaf temperature is within ±2-3 °C of air temperature (Bierhuizen and Slatyer 1965), Tanner (1981) and Sinclair et al. (1984) modified equation (2) to calculate the transpiration-use efficiency coefficient of a crop canopy (K_c) :

$$K_c = \left[\frac{Y}{T}\right] D_a \quad (3)$$

where K_c = transpiration-use efficiency coefficient (Pa), Y = crop above-ground biomass production (kg ha^{-1}), T = total canopy transpiration per area during growth to harvest (kg ha^{-1}), and D_a = seasonal average daytime vapor pressure deficit (Pa).

Tanner and Sinclair (1983) modified the equation (3) further by employing a number of simplifying assumptions. They assumed that the ratio between the internal (leaf) and the external (bulk air) concentration of CO_2 (c_i/c_a) is a constant (0.7 for C_3 crops and 0.3 for C_4 crops), and when the leaf area index is greater than 3, leaves are separated into either shaded or sunlit, and shaded leaf temperatures are assumed to be equal to air temperature. Equation 4 is:

$$K_c = 1.6 \text{ abc } P_a \frac{L_D}{L_T} \quad (4)$$

where, a = molecular weight ratio of carbohydrates to CO_2 (0.68), b = conversion coefficient from hexose to biomass (0.8 for crops with high accumulation of sugar or starch, 0.45 for crops with high accumulation of oil, and 0.40 for crops with high accumulation of protein), c = constant for expressing the CO_2 concentration difference (0.7 for C_3 crops and 0.3 for C_4 crops), P_a = partial pressure of CO_2 in the atmosphere (Pa), and L_D = sunlit leaf area index, L_T = effective transpiring leaf area

Most K_c values represent only shoot biomass due to the difficulty of measuring root biomass, especially in field studies. However, modeling root biomass can have a large effect on K_c values, especially when the plant is a perennial or the root is a storage or reproductive organ. Azam-Ali and Squire (2002) reported that the transpiration-use efficiency for groundnuts (*Arachis hypogaea*) almost doubled by including the roots in the biomass measurement.

There are two different approaches to calculate K_c at the field level. The first defines K_c as the slope of the linear regression between total biomass and the daily integration of the quotient between transpiration and daytime air vapor pressure deficit (Tanner 1981; Condon et al. 1993; Marcos 2000; Kemanian et al. 2005). The second calculates K_c as the product of Y/T times the seasonal average of day time air vapor pressure deficit (Equation (2)). (Hubick and Farquhar 1989; Siddique et al. 1990; Gregory et al. 1992; Doyle and Fischer 1979; Connor et al. 1992; Meinke et al. 1997; Angus and van Herwaarden 2001; Foulkes et al. 2001). It is difficult to compare both approaches as none of the experiments have calculated the K_c values using both approaches. It is clear from the literature review that the first approach was used in field experiments and the second approach was used in pot experiments. In this research, K_c values were calculated using the second approach.

Total transpirable soil water (TTSW) is the difference between field capacity and permanent wilting point, and represents the water available in a soil to support plant transpiration (Sinclair and Ludlow 1986). The quantity of TTSW varies among soils and depends primarily on soil texture and organic matter (Colman 1947). However, for a given soil there can be additional variation in the TTSW depending on the plant species and its ability to extract water, and the effect of environmental conditions such as temperature, humidity, wind speed and radiation (Sinclair et al. 2005). TTSW can be defined either thermodynamically or based on plant physiological response.

The thermodynamic definition of field capacity is the bulk water content retained in soil at -33 kPa of soil matric potential, and the definition for permanent wilting point is the bulk water content retained in soil at -1500 kPa of soil matric potential. Thermodynamic measurements of field capacity and permanent wilting point of soil samples are made by applying air pressures of 33 kPa and 1500 kPa using pressure plate apparatus (Richards and Weaver 1943; Cassel and Nielsen 1986). The main advantage of thermodynamic measurements is that they are relatively easy to measure. An important limitation of the thermodynamic approach is that it does not account for the differential abilities across plant species to extract water from a soil, and thus may lead to either overestimation or under estimation of TTSW for the permanent wilting point (Granier et al. 2000; Bernier et al. 2002; Girona et al. 2002, Sinclair and Ludlow 1985; Sinclair et al 2005).

The physiological definition of field capacity (FC) is the upper boundary of water held in the soil (Colman 1947). The field capacity represents water held in micropores of soil after water has drained from the macropores due to gravitational pull. The field capacity of a particular soil depends primarily on soil texture and is considered consistent irrespective of the plant species and environmental conditions (Colman 1947; Sinclair et al. 2005). In the field, the velocity of the drainage depends on the hydraulic conductivity of the soil, and drainage is faster for coarse-textured soils compared to fine-textured soils. Hence, the required time after saturation to measure the field capacity should vary based on the texture of a soil (Zotarelli et al. 2010). In pot studies, field capacity was determined by weighing pots that had been allowed to drain for 36 hours after having been saturated (Sinclair and Ludlow 1986, Sinclair et al. 2005).

The physiological definition of permanent wilting point (PWP) is the lower boundary of water held in the soil below which plants wilt and fail to recover when placed in a humid chamber (Soil Science Society of America 1997; Richards and Weaver 1943). At PWP, a soil still holds water, sometimes in relatively large quantities, but it is held so tightly that the plant cannot extract it. Sunflower was used as an indicator species in wilting studies by Veihmeyer and Hendrickson (1928), Furr and Reeve (1945), and Briggs and Shantz (1912) and the procedures were standardized as the sunflower method. In the sunflower method, pot-grown plants are watered until the third set of leaves appears, at which time the watering ceases and the plants are bagged at the base of the stem. Then plants are kept in an environment with low evaporative demand until all three sets of leaves wilt. To ensure that the wilting is permanent, plants are placed overnight in a dark humid chamber. If the leaves remain wilted in the morning, plants are considered permanently wilted and the soil water content is determined and defined as the permanent wilting point. There are several additional approaches that can be used to measure physiological PWP. In pot studies, the permanent wilting point can be determined by weighing pots daily until the transpiration rates of water-stressed plants falls below 10% of well-watered plants (Sinclair et al 2005). However, measuring permanent wilting point in the field is difficult because of different rooting depths, complex soil horizons, varied cropping patterns, and environmental demands can cause large variations in the measured values (Ratliff et al. 1983; Ritchie 1981, Cabelguenne and Debaeke 1998).

The fraction of transpirable soil water (FTSW) represents the percentage of total transpirable soil water remaining in a soil. The FTSW can be used to impose different levels of water stress on a plant or to reference changes in plant transpiration as a soil is allowed to dry from field capacity toward the PWP (Sinclair et al 2005; Ray and Sinclair 1998; Sinclair et al. 2007; Sinclair and Ludlow 1986). Plants that are subjected to water stress typically are smaller, have reduced leaf expansion (Boyer 1970; Connor and Sadras 1992; Takami et al. 1981), reduced stomatal conductance (Connor and Sadras 1992; Gimenez and Fereres 1986; Hernandez and Orioli 1985; Kiani et al. 2007) and reduced transpiration compared to well-watered controls. Dry down studies show the FTSW thresholds where transpiration rates decline (Table 2). In these studies plants maintained rapid transpiration rates and growth until reaching the reported FTSW threshold, at which point the rate of transpiration per unit mass declines. With few exceptions, the FTSW threshold where transpiration declines on a mineral soil occurs between 0.20 and 0.45 (Table 2).

Knowing K_c values theoretically allows one to compare transpiration use efficiencies among plant species. However, K_c is not a true constant because it represents a site specific relationship between a plant and a given environment. Hence, comparisons of K_c among species when the plants are grown in different environments must be made cautiously. In addition, extrapolating K_c values to other environments must also be done cautiously. Some of the reasons why K_c varies across environments may include: partial pressures of CO_2 inside the leaf airspaces and outside atmosphere (P_i/P_a) which explains the differences between C_3 and C_4 plants and the level at which K_c was estimated (leaf level versus. canopy level) (Condon et al. 1993, 2002); the time of year and associated variation in vapor pressure deficit (Kemanian et al. 2005); growth stages of the crop (vegetative versus reproductive) (Angus and van Herwaarden 2001); exclusion of root biomass in calculating K_c (Simmonds and Azam-Ali 1989; Azam-Ali et al. 1989); and level of water stress (water-stressed versus irrigated). The transpiration-use efficiency of water-stressed crops was reported to be higher than irrigated crops (Vos and Groenwold 1989 in potato; Bruck et al. 2000 in pearl millet), but K_c values were not calculated in these experiments. Hubick and Farquhar (1989) reported that the K_c of water stressed barley was greater (5.9 Pa) than of irrigated barley (4.7 Pa).

Based on our understanding of the principles and issues described above, we hypothesized that (1) K_c values would differ when weeds were subjected to water-stressed vs. water-sufficient conditions and (2) K_c values would differ between vegetative growth and complete life cycle growth. The objectives of this research were to: (1) determine the K_c of seven weed species, (2) determine the effect of fraction of transpirable soil water level on K_c and (3) determine the effect of growth stage on K_c for these seven species. We chose five common winter annual weeds, field pennycress, pinnate tansymustard, henbit, shepherd's-purse, and Carolina foxtail, one perennial, dandelion, and one summer annual, common lambsquarters. Common lambsquarters germinates early in the spring, often before crop planting and its life cycle overlaps with most winter annual weeds. Dandelion is a perennial, occurs in many no-till fields, and grows actively during the same time that winter annual weeds complete their life cycles.

MATERIALS AND METHODS

Greenhouse Conditions

Experiments were conducted from May 2008 to August 2010 in greenhouses located at the University of Nebraska-Lincoln, in Lincoln, NE. A Watchdog model 2475 plant growth station[1] was installed at a height of 5 ft at the center of the greenhouse to record air temperature, relative humidity and photosynthetically active radiation every 30 minutes. The greenhouse was maintained at 25/20 (±3.3/5.7) C day/night temperatures and light was supplemented using sodium halide lamps to ensure a 14 h day length. Saturation vapor pressure (VP_{sat}), actual vapor pressure (VP_{air}), and vapor pressure deficit (VPD) were calculated using the following equations (Prenger and Ling 2000).

$$VP_{sat} = 0.60178 * \mathrm{EXP}((17.269 * \mathrm{T})/(\mathrm{T} + 237.3)) \quad (4)$$

$$VP_{air} = VP_{sat} \times RH \div 100 \quad (5)$$

$$VPD = VP_{sat} - VP_{air} \quad (6)$$

Where RH is relative humidity (%) and T is temperature (C).

Experimental Materials

The seven weed species used in this research were field pennycress (*Thlaspi arvense* L.), common lambsquarters (*Chenopodium album* L.), pinnate tansymustard (*Descurainia pinnata* (Walt.) Britt.), dandelion (*Taraxacum officinale* G.H. Weber ex Wiggers), henbit (*Lamium amplexicaule* L.), shepherd's-purse (*Capsella bursa-pastoris* (L.) Medik.), and Carolina foxtail (*Alopecurus carolinianus* Walt.). Seed of Carolina foxtail, dandelion and common lambsquarters was collected from fields of the Lincoln Agronomy Farm, Lincoln, NE. Seed of henbit, pinnate tansymustard, field pennycress and shepherd's-purse was obtained from Herbiseed[2]. Two different pot sizes were used based on the growth habit of each species. The small pots had a volume of 1.05 L and were used for dandelion, henbit, shepherd's-purse and Carolina foxtail. The large pots had a volume of 2.65 L and were used for field pennycress, common lambsquarters and pinnate tansymustard. The potting mixture was prepared by thoroughly mixing soil, sand and perlite in an 8:1:1 volumetric ratio. The soil used in the potting mixture had a clay loam texture and a pH of 6.7. Perlite is a low density material that expands upon soaking and helps prevent water loss and soil compaction. Pots were filled with either 1300 g (small pots) or 3300 g (large pots) dry potting mixture.

The bulk density of potting mixture was determined by taking a soil core of 18 cm^3 and drying the sample in an oven at 105 C for 48 h and then weighing the core. Bulk density was calculated as the ratio between oven dry weight of the sample and volume of the soil core. The same procedure was performed twice, once before watering the pots and again at the end of the experiment. The bulk density of potting mixture before watering the pots and prior to plants growing in them was 1.34 g cm^{-3}. When measured after plants had grown in them the bulk density was 1.21 g cm^{-3}. A bulk density of 1.34 g cm^{-3} used to calculate the volumetric soil water content at field capacity and permanent wilting point.

Total Transpirable Soil Water.

The total transpirable soil water was calculated for each species by measuring the field capacity of the potting mixture and the species specific physiological permanent wilting point. Experiments were conducted as a completely randomized design experiment with 4 replications for each species.

Field capacity (θ_{fc})

Field capacity of the potting mixture was measured using 4 replications per pot size. Pots were watered to saturation, allowed to drain for 36 hours, and then weighed. The mass of water at field capacity was the difference between the weight at field capacity and the dry weight of the soil. Volumetric soil water content was calculated using:

$$\theta = \frac{M_l}{M_s}\rho_s \qquad (8)$$

where M_l is the mass of water (g), M_s is the mass of dry soil (g), and ρ_s is the bulk density of the mixture (1.34 g cm^{-3}).

Permanent Wilting Point (θ_{pwp})

A polyethylene bag was placed in each pot before the potting mixture was added. Seeds were planted by species in separate pots. Pots were watered adequately to maintain plant growth. Once the plants attained a predetermined leaf number (Table 3), they were thinned to one plant per pot and the pots were watered to reach field capacity. The polyethylene bag was then sealed at the base of the plant to limit water loss to transpiration only. After bagging, watering was completely withheld and pots were weighed at regular intervals until the plants reached permanent wilting point. Plants were considered permanently wilted when the pot mass did not change for 4 consecutive days. Table 3 gives the number of days between bagging and permanent wilting for each species. Volumetric soil water content at the PWP (θ_{pwp}) was calculated using equation 7.

Total transpirable soil water was calculated as the mass difference of pots between field capacity and permanent wilting point. Different fractions of TTSW were calculated to impose various levels of water stress for the transpiration-use efficiency coefficient study (Table 3).

The field capacity and permanent wilting point of the potting mixture were also determined thermodynamically. Three composite samples of potting mixture were sent to a soil testing lab[3] to determine the gravimetric water content held against 0, 33, 66, 100, 300, 900, and 1500 kPa matric pressure. Gravimetric water content was converted to volumetric water content using a bulk density of 1.34 g cm^{-3} and a soil water retention curve was modeled (Burgert 2009) by fitting a three-parameter exponential decay function to the data (Fig. 1).

Transpiration-use Efficiency Coefficients

Experiments were conducted to determine the effect of fraction of transpirable soil water (FTSW) and plant growth stage on the transpiration-use efficiency coefficient (K_c), leaf area (LA), cumulative transpiration (T), dry matter partitioning (Y_b, Y_a and Y), water use (WU), transpiration-use efficiency (TE), transpiration per unit leaf area (TLA), and leaf area ratio (LAR) of the seven weed species listed above. The experimental design was completely randomized with 6 replications two factors: four FTSW levels (0.3, 0.4, 0.7, and 1) and two harvest times (first bloom and complete life cycle). Pot location was re-randomized weekly on the greenhouse bench. Due to space and time constraints, all seven species were not tested simulataneously – no more than 4 species were grown at a time. The experiment was conducted twice for each species.

Until the bags were sealed around the plant stem, the same procedures described above for the Total Transpirable Soil Water experiment were followed. Immediately prior to sealing the bags, each pot was watered to reach the required pot mass for the assigned FTSW level. At the time of bagging, a 5 ml plastic syringe was inserted through the bag and the junction was taped to maintain the seal. From this time forward the syringe was used to water the plants daily to maintain the required pot mass. Pots were weighed daily at the same time and in the same order for the duration of the experiment and daily transpiration was calculated as the difference in mass on successive days. Daily transpiration that occurred prior to bagging was estimated for each plant by fitting a second order polynomial function to daily transpiration during the first 20 days of measurement after bagging plants and back-calculating to the time of emergence (Fig. 2). Cumulative transpiration (T) per plant was calculated by summing daily transpiration throughout the experiment for each plant.

Plants were harvested at first bloom or seed maturity. First bloom or vegetative stage was defined as the time when the first flower (dandelion) or set of flowers (field pennycress, common lambsquarters, pinnate tansymustard, henbit, and shepherd's-purse) or seed head (Carolina foxtail) was produced on the plant. Seed maturity or complete lifecycle was defined as the time when seed from all the flowers was mature and ready to drop from the plant, hence it includes vegetative growth too. At harvest, plants were cut at the soil surface and separated into leaf and stem tissue. The roots were washed free of soil by running tap-water over them. Leaves, stems and roots were dried separately at 60 C to a constant mass. The dry biomass was summed as total biomass (Y), biomass-below ground (Y_b), or biomass-above ground (Y_a).

Senesced leaves were collected at regular intervals and their leaf area was measured using an area meter[4]. The leaf area of leaves attached to the plant at harvest was also measured. Total leaf area is the sum of leaf area at harvest and the leaf area of senesced leaves measured prior to harvest.

The leaf area ratio was calculated using equation 9:

$$\mathrm{LAR} = \frac{\mathrm{LA}}{\mathrm{Y}} \qquad (9)$$

where, LAR = leaf area ratio ($cm^2\ g^{-1}$), LA = total leaf area produced by the plant from emergence to harvest (cm^2), and Y = total biomass (g). The LAR measurements in this study differ from form LAR measurements taken in most field studies because it include senesced leaves. However it did allow us to account for all the tissue produced by the plant.

The Transpiration per unit leaf area was calculated using equation 10:

$$\mathrm{TLA} = \frac{\mathrm{T}}{\mathrm{LA}} \qquad (10)$$

where, TLA = transpiration per unit leaf area ($g\ cm^{-2}$), T = cumulative transpiration (g), and LA = total leaf area from emergence to harvest (cm^2). TLA values should be interpreted with care because it integrates the total leaf area over the plants entire life cycle rather than leaf area on a particular day. TLA measurements described elsewhere typically describe transpiration per day per LA on the plant on the day of the transpiration measurement.

Whole plant transpiration-use efficiency was calculated using equation 11:

$$\mathrm{TE} = \frac{\mathrm{Y}}{\mathrm{T}} \qquad (11)$$

where, TE = whole plant transpiration-use efficiency (g biomass g^{-1} water transpired), Y = total biomass (g), and T = cumulative transpiration (g).

Shoot transpiration-use efficiency was calculated using equation 12:

$$STE = \frac{Y_A}{T} \qquad (12)$$

where, STE = shoot transpiration-use efficiency (g biomass g^{-1} water transpired), Y_A = total biomass (g), and T = cumulative transpiration (g).

Whole plant water conversion to plant biomass was calculated using equation 13:

$$WC = \frac{T}{Y} \qquad (13)$$

where, WC = whole plant water conversion (g water transpired g^{-1} biomass), T = cumulative transpiration (g), and Y = total biomass (g).

Shoot water conversion to plant biomass was calculated using equation 14:

$$SWC = \frac{T}{Y_A} \qquad (14)$$

where, SWC = shoot water conversion (g water transpired g^{-1} biomass), T = cumulative transpiration (g), and Y_A = total biomass (g).

The whole plant transpiration-use efficiency coefficient was calculated using equation 3:

$$K_c = \frac{Y}{T} D_a \qquad (3)$$

where, K_c = whole plant transpiration-use efficiency coefficient (Pa), Y = total biomass (g), T = cumulative transpiration (g), and D_a = seasonal average daytime vapor pressure deficit (Pa).

The shoot transpiration-use efficiency coefficient was calculated using equation 15:

$$SK_c = \frac{Y_A}{T} D_a \quad (15)$$

where, SK_c = shoot transpiration-use efficiency coefficient (Pa), Y_A = shoot biomass (g), T = cumulative transpiration (g), and D_a = seasonal average daytime vapor pressure deficit (Pa).

Seasonal minimum, maximum, and average daytime vapor pressure deficit and number of days before first bloom and seed maturity during both experimental runs for each weed species are presented in table 4.

Statistical Analysis

Data were analyzed using the SAS System for Windows, Version 9.2[5]. Data for each species were analyzed separately. Leaf area, cumulative transpiration, dry matter partitioning, water conversion, transpiration-use efficiency, leaf area ratio, transpiration per unit leaf area and the transpiration-use efficiency coefficient were compared among experimental runs by ANOVA using the MIXED procedure in SAS. Experiment run, FTSW level and growth stage were considered as fixed variables. If the three-way interaction was significant, results were reported by experiment. Differences among treatment means were compared using the Tukey adjustment at $p = 0.05$.

RESULTS AND DISCUSSION

Total Transpirable Soil Water

Volumetric water content at field capacity (θ_{fc}) was 0.376 for large pots and 0.352 for small pots, when measured after allowing the pots to drain for 36 h after being saturated (Table 3). Based on the thermodynamic measurement of 33 kPa, the volumetric field capacity was 0.351 (Fig 1). The volumetric water content at permanent wilting point (θ_{pwp}), defined as the point when pot weight did not change over 4 days, differed between species and ranged from 0.051 (field pennycress) to 0.115 (henbit). Volumetric water content measured using a pressure-plate apparatus at 1500 kPa was 0.167 (Fig 1). This suggests that each of these species was able to extract water beyond 1500 kPa of soil matric pressure.

The field capacity for a given soil is relatively constant (Colman et al. 1947; Ratliff et al. 1983), but the permanent wilting point is influenced by the interaction of plant species and soil characteristics (Sinclair et al. 2005; Sinclair and Ludlow 1986). Our results show that permanent wilting point should be calculated using physiological definitions to account for variation among species.

Field pennycress

Field pennycress K_c values were greater during the vegetative stage compared to the complete life cycle at all FTSW levels (Figure 3A). However, the plants responded differently to FTSW levels depending on growth stage (Table 5). During vegetative growth, K_c values decreased as FTSW level increased from 0.4 to 0.7, suggesting that pennycress used water more efficiently under water stressed conditions (Fig. 3A). In contrast, the complete lifecycle K_c values increased as FTSW level increased from 0.4 to

0.7, suggesting plants did not use water as efficiently when water-stressed during reproductive stages (Fig. 3A).

The complete lifecycle K_c values integrate water use during both vegetative and reproductive growth stages. When K_c values differ between growth stages the changes that take place in water use characteristics during reproductive growth may be understood to be substantial. The differential response of K_c to FTSW level between vegetative and reproductive growth reflects a lack of biomass accumulation at 0.3 FTSW. Field pennycress completed its life cycle and produced seed at 0.3 FTSW, but did not accumulate new biomass after flowering while still continuing to transpire. This drastically reduced K_c values for the complete lifecycle (Table 6). Plants at FTSW levels 0.4 and greater accumulated new biomass after flowering.

Seeds of field pennycress are rich in oil content (36%) and are being considered as an oil source for biodiesel production (Evangelista et al. 2010). The conversion coefficient from hexose to oil (0.45) is less than the conversion to structural carbohydrates (0.8). The large decline in K_c between vegetative and reproductive growth is because most of the biomass accumulated during reproductive stages is stored as oil, consequently biomass gain per unit water transpired is less.

Field pennycress biomass increased as FTSW levels increased (Table 6). Similarly, leaf area increased as FTSW levels increased (Table 6). Field pennycress typically has a determinate growth habit, which means that new leaf production stops once flowering begins. However, in an occurrence that we do not have an explanation for, leaf area in the 0.7 FTSW level increased after flowering during experiment run 1 (Table 6).

Root growth (Y_b) was not consistent between harvest times, nor was it consistent across FTSW levels (Table 6). At FTSW levels 0.7 and 1.0, shoot growth relative to root growth was much greater at seed maturity compared to first bloom (Table 6). This affected the relationship between whole plant K_c and shoot K_c values (Figure 3A, 3B). The exclusion of root biomass reduced K_c values more at first bloom than at seed maturity.

Experiment run influenced the interaction of FTSW and time of harvest for Y_a, Y, T, LA, LAR and TLA (Table 5). The results of those variables are presented as means of individual experiment runs (Table 6) and the results of TE and WC are presented as combined means of both experiment runs (Table 7).

Common lambsquarters

Common lambsquarters K_c values were greater during vegetative growth than during the complete life cycle (Table 8, Fig. 4), similar to field pennycress. Seeds of common lambsquarters are rich in protein (22.9%) (National Academy of Sciences 1971), and the conversion coefficient from hexose to protein (0.40) is less than the conversion to structural carbohydrates (0.8) (Penning de vries 1975b). The decline in K_c between vegetative and reproductive growth is likely because much of the biomass accumulated during reproductive stages is protein. K_c values decreased from 0.3 to 0.7 FTSW during both vegetative and complete life cycle measurements (Figure 4), suggesting common lambsquarters is well adapted to growing under water-stressed conditions in both vegetative and reproductive stages.

Total biomass increased as FTSW level increased from 0.3 to 0.7 (Table 9). Total biomass did not increase between flowering and seed maturity at 0.3 FTSW, but did increase at 0.4, 0.7 and 1.0 FTSW levels, also similar to field pennycress (Table 9). Common lambsquarters is a short-day species and is a photoperiodic indeterminate (Williams 1963). New leaf production can continue after flowering depending on resource availability. Reproductive development can begin shortly after emergence if conditions are unfavorable which enables it to complete its life cycle quickly and produce mature seeds. Leaf area (Table 10) did not change between vegetative and complete life cycle growth stages except a decrease at 0.7 and 1.0 FTSW during experimental run 2.

Shoot K_c values were numerically smaller than whole plant K_c values, but were not statistically different (Figures 4A, 4B). Experiment run influenced the interaction between FTSW and time of harvest for LA, T, LAR, TLA and Y_b (Table 8). Results of those variables are presented as means of individual experiment runs (Table 10) and results of TE, Y_a, Y and WC are presented as combined means of both experiment runs (Tables 11 and 12).

Pinnate tansymustard

Pinnate tansymustard K_c values were not influenced by time of harvest (Table 13, Figure 5) which means that pinnate tansymustard converted transpiration to biomass at similar rates during vegetative and complete life cycle growth stages. K_c values decreased from 0.3 to 0.7 FTSW (Fig. 5), suggesting that pinnate tansymustard may be relatively drought tolerant.

Total biomass and cumulative transpiration increased as FTSW increased during both vegetative and complete life cycle growth stages (Table 14). Total biomass did not increase between first bloom and seed maturity at the FTSW levels 0.3 and 0.4, but did increase at FTSW levels 0.7 and 1.0. This was somewhat surprising, because pinnate tansymustard has a determinate growth habit, which means new leaf production ceases at flowering. Typically, pinnate tansymustard plants produce a low rosette of basal leaves before bolting. But the plants growing at FTSW levels 0.7 and 1.0 produced more than one flowering branch and more leaves compared than plants grown at FTSW levels 0.3 and 0.4 (visual observation).

There was little difference between shoot K_c (Figure 5B) and whole plant K_c values (Figure 5A) because root biomass (Y_b) represented a relatively small percentage of total biomass (Table 15). Experiment run significantly influenced the interaction between FTSW and time of harvest for biomass-belowground (Y_b) (Table 13). Hence, the results of Y_b are presented as means of individual experiment runs (Table 15) and the results of WC, TE, LA, Y_a, TLA and LAR are presented as combined means of both experiment runs (Table 16-18).

Dandelion

Dandelion K_c values increased as FTSW level increased (Table 19, Figure 6A), suggests that dandelion is relatively susceptible to drought stress. During vegetative growth K_c values increased from 0.3 to 0.7 FTSW, but during the complete life cycle they increased from 0.3 to 1.0 FTSW (Fig 6). Whole plant K_c values were similar between the vegetative and complete life cycle growth stages (Figure 6A). The duration of time between first bloom and seed maturity was relatively short (7-10 days). In addition, the seed biomass of dandelion is small compared to the total plant biomass because a high proportion of the biomass is carbohydrate reserves stored in the root. Consequently, there were no differences in K_c or transpiration between first bloom and seed maturity.

Dandelion biomass increased as FTSW level increased. Biomass did not increase between first bloom and seed maturity except at 1.0 FTSW (Table 20), likely due to the relatively brief time between flowering and seed maturity. Some plants grown at 1.0 FTSW produced more than one flower stem, but no plants at the lower FTSW levels produced multiple stems. Similar to total biomass, total leaf area increased as FTSW levels increased (Table 21). The length of time required for dandelion plants to flower was longer at 0.3 FTSW (139-277 days after treatments were imposed) compared to plants grown at 0.7 or 1.0 FTSW (70-166 days after treatments were imposed) (Table 4). The duration from imposing treatments to flowering was variable among dandelion individuals at all FTSW levels.

Shoot K_c values (Figure 6B) were greatly reduced compared to whole plant K_c values (Figure 6A). At least 50% of the total biomass of dandelion in this experiment was stored in the taproot (Table 20), underscoring the importance of including root biomass when calculating the K_c of species that have large percentage of biomass stored belowground. Azam-Ali and Squire (2002) reported that the transpiration-use efficiency for groundnuts (*Arachis hypogaea*) almost doubled by including the roots in the biomass measurement. Experiment run did not influence the interaction of fraction of transpirable soil water and time of harvest of any response variable (Table 19). Results of LA, TE, WC, Y_b, Y_a, TLA and LAR are presented as the combined means of experiment runs (Table 20-22).

Henbit

Henbit K_c values did not differ among FTSW levels during the vegetative growth stage (Figure 7A). However, during the complete life cycle, K_c values declined as FTSW levels increased from 0.3 to 0.7 during the complete life cycle (Table 23, Figure 7A). , suggesting that henbit may be relatively tolerant to drought. K_c values were greater at first bloom than at seed maturity harvests at 0.3 FTSW. In contrast, K_c values were smaller at seed maturity harvest than at first bloom for the 0.7 and 1.0 FTSW levels (Fig. 7A).

Henbit is a tap-rooted winter annual in the Lamiaceae (mint) family. It has an indeterminate growth habit, and continues to produce leaves and new flowers after first bloom when resource availability is favorable. Henbit plants flower relatively quickly after emergence. In this study, plants at all FTSW levels flowered approximately 25 days after emergence. This likely contributed to the similar K_c values measured at all FTSW levels at first bloom. Similarly, total biomass did not differ among FTSW levels during vegetative growth (Table 24). Total biomass did not increase between flowering and seed maturity except at 1.0 FTSW during experiment run 1 (Table 24), but increased as FTSW level increased from 0.3 to 1.0 during the complete life cycle (Table 24). The interaction in K_c values between vegetative and complete life cycle may be explained in part by how the indeterminate habit of henbit was affected by FTSW level. Plants at the 0.3 and 0.4 FTSW levels produced seed approximately 7 days after first bloom, but did not produce additional flowers. Plants at the 0.7 and 1.0 FTSW levels continued to produce flowers even after mature seed had formed. Seed of henbit is rich in essential volatile oils (Flamini et al. 2005). The conversion coefficient from hexose to oil (0.45) is less than the conversion to structural carbohydrates (0.8) (Penning de vries 1975b). The decline in K_c between vegetative and reproductive growth at 0.7 and 1.0 FTSW was because much of the biomass during reproductive stages is accumulated as oil.

Shoot K_c values (Figure 7B) were lower than whole plant K_c values (Figure 7A) numerically, but not statistically. Experiment run significantly influenced the interaction of fraction of transpirable soil water and time of harvest for Y_a, Y, T, LA, TLA and LAR (Table 23). The results of those variables are presented as means of individual experiment runs (Table 24) and the results of TE, WC, Y_b are presented as combined means of both experiment runs (Table 25 and 26).

Shepherd's-purse

Shepherd's-purse K_c values greater at first bloom than at seed maturity for FTSW levels 0.3 and 0.4 (Table 27, Figure 8A). K_c values were similar at 0.7 and 1.0 FTSW at the first bloom and seed maturity harvest times (Figure 8A). Within a harvest time (first bloom or seed maturity), K_c values were similar for all FTSW levels, suggesting that shepherd's-purse is neutral in its adaptation to water-deficit stress. Shepherd's-purse is a winter annual in the Brassicaceae family. Plants produce a rosette of lobed basal leaves from where the flower stem emerges. It has a determinate growth habit and new vegetative growth ceases at flowering. Plants grown under water deficit conditions (0.3 and 0.4 FTSW) required more days before flowering and producing seed compared to the plants grown under water sufficient conditions (0.7 and 1.0 FTSW) (personal observation). Total biomass did not differ between FTSW levels during the first bloom (Table 28). However, total biomass increased as FTSW level increased from 0.3 to 1.0 at the time of seed maturity (Table 28). Plants at 0.3 and 0.4 FTSW did not statistically increase biomass between first bloom and seed maturity (Table 28). The decline in K_c between vegetative and reproductive growth at 0.3 and 0.4 FTSW may have been partially due to limited biomass accumulation while transpiration continued. Seed of shepherd's-purse is rich in oil content (27.8-39.7%) (Mukherjee et al. 1984; Moser et al. 2010). This may also have contributed to the lower K_c values at complete life cycle for 0.3 and 0.4 FTSW. However, one may have expected some reduction at the 0.7 and 1.0 FTSW levels, but this did not occur

Shoot K_c values were numerically lower than whole plant K_c values, but were statistically similar. Experiment run influenced the interaction of fraction of transpirable soil water and time of harvest for leaf area ratio (LAR) (Table 27). The results of LAR are presented as means of individual experiment runs (Table 29) and the results of TE, WC, Y_b, Y_a, T, TLA and LA are presented as combined means of both experiment runs (Table 28 and 30).

Carolina foxtail

The response Carolina foxtail K_c values to FTSW level and life cycle was not consistent across experiment runs (Table 31). K_c values increased as FTSW level increased from 0.3 to 0.7 during vegetative and complete life cycle growth stages suggesting that Carolina foxtail is drought susceptible (Fig. 9 and 10). K_c values were greater at seed maturity than at first bloom for 0.3 FTSW during run 1 and 0.3 and 0.4 FTSW levels during run 2 (Fig. 9 and 10). This differs from all the other species we studied, with the exception of henbit at 0.3 FTSW. In contrast, K_c values but did not differ between vegetative and complete life cycle at 0.7 and 1.0 FTSW levels with the exception of lower K_c values for complete life cycle at 1.0 FTSW level during experiment run 1. We were unable to identify any errors in methodology that may have contributed to this variation.

Carolina foxtail biomass and leaf area increased as FTSW increased (Table 32 and 33). Flowering was delayed for plants grown at 0.3 and 0.4 FTSW compared to 0.7 and 1.0 FTSW. Plants at 0.3 and 0.4 FTSW produced only one seed head, while those at higher FTSW levels produced multiple seed heads.

Carolina foxtail is more susceptible to drought stress than many of the other species we studied.

Experiment run influenced the interaction between fraction of transpirable soil water and time of harvest for TE, WC, Y_a, T, and LA (Table 31). The results of those variables are presented as means of individual experiment runs (Table 32). Results of Y_b, LAR, and TLA are presented as combined means of experiment runs (Table 33 and 34).

SUMMARY

This research is the first we know of determine K_c values of these weed species. Other K_c values reported are for crop species. Wheat K_c values ranged from 2.80 (Gregory et al. 1992) to 6.7 Pa (Angus and van Herwaarden 2001) when grown at different locations. Not all this variability should be attributed to genotypic variation. Some of the variation can be attributed the inconsistent calculation methods (Kemanian et al. 2005; Tanner 1981). Condon et al. (1993) found a correlation between genotypic variation in K_c and ^{13}C discrimination in wheat. It is assumed that the K_c, rather than a constant, could be a function of leaf-to-air vapor pressure deficit at the leaf level (Kemanian et al. 2005; Condon et al. 2002). By conducting this research in greenhouse experiments, we minimized some of the variation in vapor pressure deficit and common in field research. In the field, calculation of water loss due solely to transpiration is difficult because it can be difficult to account for factors such as infiltration, runoff, precipitation, evaporation and deep percolation. By preventing evaporation and leaching through the use of polyethylene bags we eliminated all factors responsible for water loss excluding the transpiration.

This is the first research we are aware of that determines the effect of water stress (different FTSW levels) and time of harvest (growth stage) on K_c values. Previous FTSW studies allowed plants to progressively deplete soil moisture to determine the threshold FTSW where transpiration starts declining. Angus and van Herwaarden (2001) reported a higher K_c values postanthesis in wheat compared to preanthesis. They reported that this variation was due to the higher vapor pressure deficit during postanthesis.

Our results show that the K_c values are influenced by fraction of transpirable soil water.. Species that appeared to be relatively drought-tolerant (K_c values increased as FTSW levels decreased) included common lambsquarters and pinnate tansymustard. Species that appeared to be relatively drought-susceptible (K_c values increased as FTSW level increased) included dandelion and Carolina foxtail. K_c values for Shepherd's-purse were not affected by FTSW level. K_c values of henbit and field pennycress responded differently to FTSW level depending on whether the plants were in vegetative or reproductive growth stages. Field pennycress was more drought tolerant during vegetative than reproductive growth, but henbit was more drought tolerant during reproductive growth stages. Further research is required to understand the physiological mechanisms responsible how K_c values respond to FTSW levels, which may help in developing drought resistant plants.

Reproductive growth can have a large influence on K_c values. This may be in part due to differences in the carbohydrate:oil:protein ratio of the seed relative to the plants stems and leaves. For example, protein-rich common lambsquarters and oil-rich field pennycress and henbit seeds resulted in lower K_c values for the complete life cycle relative to the vegetative growth stage. In contrast, for pinnate tansymustard and dandelion, K_c values did not change between first bloom and seed maturity time of harvest. One of the more surprising results was that K_c values of Carolina foxtail (0.3 FTSW in experiment run 1 and 0.3 and 0.4 FTSW in experiment run 2) were greater for the complete life cycle than during vegetative growth at 0.3 and 0.4 FTSW. Seed composition undoubtedly has an influence on K_c values, but there may be other physiological mechanisms that affect water use efficiency during reproductive growth stages.

Our data also show that excluding root dry weight has only a minor effect on the K_c calculation, unless the root represents a major storage organ for the plant, as was the case for dandelion.

Understanding how plants use water, and how to help them use water more efficiently, will be critical to advancing agricultural productivity in a climate that appears to be increasing in the range of extremes experienced in any given location. Weeds may prove to be a source genes and traits that can be adapted to improve crop function. At the least, understanding water use of weeds will help science understand more of how weed competition for resources affects crop growth.

Sources of Materials

[1] WatchDog Model 2475 Plant Growth Station, Spectrum Technologies Inc., 12360 South Industrial Dr., East – Plainfield, Illinois 60585.

[2] Herbiseed, New Farm, Mire Lane, West End, Twyford, Berks, RG10 0NJ, UK

[3] Midwest Laboratories., 13611 B St., Omaha, NE 68144.

[4] LI-3000, LiCor Inc., 4421 Superior St., Lincoln, NE 68504.

[5] SAS Version 9.2, Statistical Analysis Systems Institute, SAS Campus Drive, Cary, NC 27512.

Table 1. Transpiration-use efficiency coefficients of crop species.

Species	K_c (Pa)	Reference
Pearl millet	3.9 – 4.6	Squire et al. (1984)
Groundnut	1.5-5.2	Ong et al. (1987)
Groundnut	3.0	Azam-Ali et al. (1989)
Bean	2.2 – 3.7	Pilbeam et al. (1995)
Soybean	1.15	Lawn (1982)
Lucerne	2-2.5	Barnard et al. (1998)
Barley	6.6 – 6.9	Kemanian et al. (2005)
Maize	9	Muchow and Sinclair (1991),
Common bean	3.26	Ogindo and Walker (2004)
Barley (water stressed)	5.9	Hubick and Farquhar (1989)
Barley (irrigated)	4.7	Hubick and Farquhar (1989)

Table 2. Fraction of transpirable soil water thresholds where transpiration rates began to decline for different species.

Species	FTSW threshold	Reference
Field pea	0.2 - 0.4	Lecoeur and Guilioni (1998)
Soybean	0.25 - 0.30	Liu et al. (2005)
Soybean	0.3 - 0.45	Sinclair et al. (2007)
Soybean	0.35	Ray and Sinclair (1998)
Soybean	0.2 - 0.3	Sinclair and Ludlow (1986)
Soybean (potting mixture)	0.6 - 0.7	Wahbi and Sinclair (2007)
Soybean (mineral soil)	0.27 - 0.34	Wahbi and Sinclair (2007)
Corn	0.36 - 0.60	Ray and Sinclair (1997)
Corn	0.3 - 0.4	Ray et al. (2002)
Corn	0.31	Ray and Sinclair (1998)
Corn (potting mixture)	0.6 - 0.7	Wahbi and Sinclair (2007)
Corn (mineral soil)	0.27 - 0.34	Wahbi and Sinclair (2007)
Corn	0.36	Schmidt et al. (2011)
Populus trichocarpa	0.35	Braatne et al. (1992)
Populus deltoides	0.45	Braatne et al. (1992)
Populus trichocarpa X *Populus deltoides*	0.6	Braatne et al. (1992)
Potato	0.2 - 0.36	Weisz et al. (1994)
Spider plant (fast-growing genotypes)	0.77	Masinde et al. (2005)

Table 2, Continued.

Spider plant (slow-growing genotypes)	0.29	Masinde et al. (2005)
Black gram	0.2 - 0.3	Sinclair and Ludlow (1986)
Woody perennials	0.23 - 0.32	Sinclair et al. (2005)
Rice	0.66	Luquet et al. (2008)
Peanut	0.22 - 0.71	Jyostna Devi et al. (2009)
Sangiovese grapevine	0.35	Bindi et al. (2005)
Cotton	0.4 - 0.5	Lacape et al. (1998)
Seashore paspalum (sandy soil)	0.10 - 0.17	Johnson et al. (2009)
Seashore paspalum (organic soil)	0.25 - 0.31	Johnson et al. (2009)
Arabidopsis (potting mixture)	0.6 - 0.7	Wahbi and Sinclair (2007)
Arabidopsis (mineral soil)	0.27 - 0.34	Wahbi and Sinclair (2007)
Velvetleaf	0.41	Schmidt et al. (2011)

Table 3. Pot weight at field capacity (FC), and permanent wilting point (PWP), the total transpirable soil water (TTSW), the volumetric water content at FC (θ_{fc}) and PWP (θ_{pwp}), the number of leaves at bagging, number of days between bagging and permanent wilting, and required pot weight for each fraction of transpirable soil water level (FTSW) for each species used in the transpiration-use efficiency experiment.

Weed Species	Pot weight (g)		TTSW (g)	θ_{fc} (v/v)	θ_{pwp} (v/v)	# of leaves at bagging	# of days before permanent wilting	Required pot weight (g) for FTSW			
	FC	PWP						0.3	0.4	0.7	1.0
field pennycress	4220	3425	795	0.376	0.051	8	57	3563.5	3643.0	3861.5	4120.0
common lambsquarters	4220	3456	764	0.376	0.064	6	46	3554.0	3610.5	3839.6	4068.7
pinnate tansymustard	4220	3447	773	0.376	0.060	8	52	3536.9	3614.2	3846.1	4078.0
dandelion	1640	1351	289	0.352	0.053	8	61	1391.6	1420.5	1507.1	1593.7
henbit	1640	1411	229	0.352	0.115	8	59	1373.6	1396.5	1465.1	1533.7
shepherd's-purse	1640	1360	280	0.352	0.062	8	55	1384.0	1412.0	1496.0	1580.0
Carolina foxtail	1640	1390	251	0.352	0.093	6	43	1376.6	1405.2	1480.3	1555.5

Table 4. Seasonal minimum, maximum, and average daytime vapor pressure deficit (kPa), and minimum and maximum duration from emergence (days) of each species used in the transpiration-use efficiency experiments.

Weed Species	Seasonal average daytime vapor pressure deficit (kPa)						Duration from Emergence (days)			
	Experiment run 1			Experiment run 2			Experiment run 1		Experiment run 2	
	Minimum	Maximum	Average	Minimum	Maximum	Average	First bloom	Seed maturity	First bloom	Seed maturity
Field pennycress	1.75	2.01	1.88	2.03	2.26	2.11	29-48	74-96	29-39	52-63
Common lambsquarters	1.65	1.99	1.83	2.06	2.26	2.17	33-34	58	31-37	64-66
Pinnate tansymustard	1.01	1.68	1.26	2.04	2.18	2.11	68-211	77-172	84-135	99-190
Dandelion	1.67	2.01	1.82	1.19	1.72	1.52	70-277	100-277	59-357	94-346
Henbit	1.42	1.99	1.67	1.21	1.47	1.32	17-25	27-45	26-33	40
Shepherd's-purse	2.06	2.16	2.11	1.57	1.97	1.76	37-140	54-177	51-159	72-159
Carolina foxtail	1.87	1.98	1.92	2.02	2.17	2.09	92-210	125-210	83-207	104-207

Table 5. Analysis of variance for field pennycress as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (Kc), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Yb), biomass-aboveground (Ya), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	0.1215	0.0014	<0.0001	<0.0001	<0.0001	<0.0001	0.4666	<0.0001	<0.0001	<0.0001	<0.0001	0.0060	0.0002
F	0.0061	0.0014	0.0081	0.0015	0.6974	0.0086	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.3483
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0200	<0.0001	<0.0001
E X F	0.9962	0.6630	0.6307	0.3763	0.5919	0.0835	0.0017	<0.0001	<0.0001	<0.0001	0.0004	0.0531	0.0011
E X H	0.5331	0.0325	0.9315	0.0676	0.0004	<0.0001	0.4458	<0.0001	<0.0001	<0.0001	0.0120	0.7243	0.0059
F X H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0643	<0.0001	0.0418
E X F X H	0.9833	0.0513	0.8196	0.3067	0.7456	0.0003	0.0387	<0.0001	<0.0001	<0.0001	0.0096	0.0006	0.0024
Experimental run 1													
F						0.4469	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.0237
H						<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0060	<0.0001	<0.0001
F X H						0.0003	<0.0001	<0.0001	<0.0001	<0.0001	0.0094	<0.0001	0.0008
Experimental run 2													
F						0.0065	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0238
H						<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.8522	<0.0001	<0.0001
F X H						<0.0001	0.0217	<0.0001	<0.0001	<0.0001	0.7197	<0.0001	0.1141

Table 6. Biomass-belowground (Y_b), biomass-above ground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), transpiration per unit leaf area (TLA) and whole plant water conversion (WC) of field pennycress as influenced by the fraction of transpirable soil water level, time of harvest and experiment run. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row for an experiment run are different at P<0.05.

Variable	Harvest	Run 1 – Fraction of transpirable soil water 0.3 (±SE)	Run 1 0.4 (±SE)	Run 1 0.7 (±SE)	Run 1 1.0 (±SE)	Run 2 0.3 (±SE)	Run 2 0.4 (±SE)	Run 2 0.7 (±SE)	Run 2 1.0 (±SE)
Y_b (g)	First bloom	0.052 a (b) (0.03)	0.161 a (ab) (0.04)	0.332 b (ab) (0.20)	0.483 b (a) (0.38)	0.050 a (b) (0.01)	0.078 a (ab) (0.02)	0.532 b (a) (0.35)	0.375 a (ab) (0.05)
	Seed maturity	0.026 a (b) (0.01)	0.140 a (b) (0.02)	0.127 a (a) (0.30)	1.297 a (a) (0.25)	0.073 a (c) (0.01)	0.325 a (bc) (0.10)	1.215 a (a) (0.45)	0.695 a (ab) (0.41)
Y_a (g)	First bloom	0.361 a (b) (0.05)	0.662 b (b) (0.20)	1.848 b (b) (0.87)	3.853 b (a) (1.21)	0.381 a (b) (0.04)	0.530 a (b) (0.12)	1.495 b (ab) (0.35)	2.870 b (a) (0.56)
	Seed maturity	0.373 a (d) (0.09)	3.304 a (c) (1.06)	17.012 a (b) (1.78)	24.169 a (a) (1.06)	0.325 a (b) (0.11)	1.217 a (b) (0.32)	9.585 a (a) (0.92)	10.468 a (a) (2.15)
Y (g)	First bloom	0.413 a (b) (0.05)	0.824 b (b) (0.24)	2.180 b (b) (0.91)	4.337 b (a) (1.58)	0.432 a (b) (0.05)	0.608 a (b) (0.10)	2.027 b (ab) (0.19)	3.245 b (a) (0.58)
	Seed maturity	0.399 a (d) (0.10)	3.444 a (c) (1.05)	18.140 a (b) (2.01)	25.861 a (a) (0.69)	0.402 a (b) (0.12)	1.542 a (b) (0.31)	10.800 a (a) (0.86)	11.163 a (a) (2.28)
T (g)	First bloom	90.02 a (b) (5.09)	191.03 b (b) (31.96)	647.01 b (ab) (280.06)	1180.32 b (a) (318.96)	110.86 a (b) (16.12)	163.1 a (b) (24.87)	671.35 b (ab) (35.77)	987.38 b (a) (215.80)
	Seed maturity	145.98 a (d) (36.80)	1234.17 a (c) (394.17)	5739.21 a (b) (511.43)	8585.46 a (a) (539.58)	181.57 a (b) (63.94)	673.33 a (b) (135.07)	4058.49 a (a) (373.60)	4332.12 a (a) (918.60)
LA (cm^2)	First bloom	41.90 a (c) (5.43)	109.44 a (c) (25.69)	410.74 b (b) (177.01)	965.37 a (a) (181.88)	40.98 a (c) (10.33)	64.80 a (c) (9.31)	420.16 a (b) (78.45)	634.26 a (a) (179.65)
	Seed maturity	35.17 a (d) (12.83)	242.70 a (c) (97.47)	774.47 a (b) (260.74)	959.81 a (a) (156.94)	16.73 a (c) (3.35)	75.32 a (c) (17.76)	379.13 a (b) (77.22)	669.76 a (a) (135.66)

Table 6, Continued…

LAR (cm^2 g^{-1})	First bloom	102.49 a (c)	135.75 a (c)	187.84 b (b)	235.15 b (a)	94.06 b (b)	108.42 b (b)	206.26 b (a)	195.5 b (a)
		(15.93)	(18.89)	(24.24)	(43.44)	(16.24)	(21.03)	(25.85)	(39.81)
	Seed maturity	86.24 a (a)	70.88 b (ab)	42.92 a (b)	37.05 a (b)	44.25 a (a)	49.99 a (a)	34.88 a (a)	63.68 a (a)
		(12.12)	(19.91)	(13.36)	(5.55)	(14.95)	(11.47)	(4.95)	(23.52)
TLA (g cm^{-2})	First bloom	2.17 a (a)	1.77 b (a)	1.60 b (a)	1.21 b (a)	2.79 b (a)	2.55 b (a)	1.64 b (a)	1.60 b (a)
		(0.26)	(0.20)	(0.18)	(0.14)	(0.46)	(0.47)	(0.25)	(0.34)
	Seed maturity	4.31 a (c)	5.63 a (bc)	8.38 a (ab)	9.17 a (a)	11.14 a (a)	9.24 a (ab)	11.00 a (a)	6.95 a (b)
		(0.71)	(2.55)	(3.88)	(1.70)	(3.80)	(2.69)	(2.05)	(3.06)
WC (g g^{-1})	First bloom		260.58 b				289.96 b		
			(47.29)				(32.61)		
	Seed maturity		343.28 a				411.81 a		
			(32.31)				(35.18)		

Table 7. Whole plant transpiration use efficiency (TE) and whole plant water conversion (WC) of field pennycress as influenced by the fraction of transpirable soil water level and time of harvest. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	First bloom	4.25 a (a) (0.57)	4.01 a (a) (0.69)	3.2 a (b) (0.36)	3.46 a (b) (0.31)
	Seed maturity	2.50 b (a) (0.35)	2.54 b (a) (0.28)	2.91 a (a) (0.33)	2.80 b (a) (0.27)
WC (g g^{-1})	First bloom	238.61 b (b) (28.07)	255.66 b (b) (39.85)	315.67 a (a) (31.13)	291.13 b (a) (23.57)
	Seed maturity	406.31 a (a) (53.87)	397.32 a (a) (43.43)	346.80 a (b) (36.55)	359.76 a (b) (32.64)

Table 8. Analysis of variance for common lambsquarters as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	0.0001	<0.0001	0.0367	0.0179	0.0046	0.0019	<0.0001	<0.0001	<0.0001	<0.0001	0.0151	<0.0001	<0.0001
F	0.0008	0.002	0.0018	0.0070	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0021
H	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.6355	<0.0001	<0.0001
E X F	0.0894	0.0113	0.1359	0.0128	0.0829	0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0551	<0.0001	0.0007
E X H	0.2039	0.0910	0.1594	0.0619	0.4729	0.0877	<0.0001	0.4048	0.1817	0.0330	0.0003	<0.0001	0.0026
F X H	0.6779	0.3931	0.6242	0.2740	0.6122	0.1042	<0.0001	<0.0001	<0.0001	<0.0001	0.5562	<0.0001	<0.0001
E X F X H	0.4050	0.5332	0.3992	0.5692	0.6050	0.4588	<0.0001	0.2411	0.1569	0.0172	<0.0001	<0.0001	0.0246
Experimental run 1													
F							0.0047			<0.0001	<0.0001	<0.0001	0.6116
H							0.0011			<0.0001	0.0570	<0.0001	<0.0001
F X H							0.0101			<0.0001	0.1417	<0.0001	0.0530
Experimental run 2													
F							<0.0001			<0.0001	<0.0001	0.3752	0.0002
H							<0.0001			<0.0001	0.0004	<0.0001	<0.0001
F X H							<0.0001			<0.0001	<0.0001	<0.0001	<0.0001

Table 9. Biomass-above ground (Y_b) and total biomass (Y) of common lambsquarters as influenced by fraction of transpirable soil water level and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y_a (g)	First bloom	0.62 a (b) (0.14)	0.93 b (b) (0.28)	4.09 b (a) (2.57)	5.35 b (a) (4.19)
	Seed maturity	1.33 a (c) (1.10)	4.24 a (b) (1.36)	15.05 a (a) (3.09)	16.94 a (a) (6.42)
Y (g)	First bloom	0.68 a (b) (0.14)	1.02 b (b) (0.32)	4.40 b (a) (2.76)	5.72 b (a) (4.46)
	Seed maturity	1.47 a (c) (1.19)	4.48 a (b) (1.50)	15.92 a (a) (3.45)	18.66 a (a) (7.56)

Table 10. Biomass-belowground (Y_b), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR) and transpiration per unit leaf area (TLA) of common lambsquarters as influenced by the fraction of transpirable soil water level, time of harvest and experiment run. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row for an experiment run are different at P<0.05.

		Fraction of transpirable soil water							
Variable	Harvest	Run 1				Run 2			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y_b (g)	First bloom	0.070 a (a)	0.121 a (a)	0.124 b (a)	0.105 b (a)	0.052 a (b)	0.053 a (b)	0.497 b (a)	0.645 b (a)
		(0.02)	(0.05)	(0.03)	(0.04)	(0.01)	(0.01)	(0.05)	(0.05)
	Seed maturity	0.067 a (c)	0.117 a (bc)	0.727 a (a)	0.612 a (ab)	0.215 a (c)	0.360 a (c)	1.025 a (b)	2.843 a (a)
		(0.02)	(0.03)	(0.62)	(0.44)	(0.05)	(0.16)	(0.13)	(0.50)
T (g)	First bloom	143.10 a (a)	236.37 a (a)	407.66 b (a)	363.99 b (a)	128.43 a (b)	176.60 a (b)	1581.63 b (a)	2187.98 b (a)
		(38.23)	(82.97)	(69.66)	(61.33)	(47.93)	(47.71)	(121.51)	(481.09)
	Seed maturity	107.70 a (b)	857.09 a (b)	3968.73 a (a)	3454.85 a (a)	575.07 a (c)	1223.77 a (c)	4621.08 a (b)	6883.55 a (a)
		(23.79)	(221.47)	(459.40)	(1341.09)	(156.75)	(286.56)	(833.79)	(1388.07)
LA (cm^2)	First bloom	34.32 a (a)	73.83 a (a)	199.62 a (a)	220.31 a (a)	28.08 a (c)	42.43 a (c)	408.49 a (b)	552.44 a (a)
		(9.36)	(29.42)	(51.93)	(33.67)	(4.11)	(2.50)	(58.84)	(145.22)
	Seed maturity	11.02 a (b)	69.26 a (b)	359.96 a (a)	352.14 a (a)	53.21 a (c)	99.28 a (bc)	226.33 b (ab)	311.46 b (a)
		(2.30)	(15.77)	265.56)	(183.12)	(16.24)	(20.63)	(92.56)	(116.63)
LAR ($cm^2 g^{-1}$)	First bloom	54.65 a (c)	65.74 a (c)	111.97 a (b)	137.74 a (a)	39.81 a (bc)	48.38 a (ab)	57.95 a (a)	55.96 a (a)
		(17.01)	(7.51)	(17.01)	(26.80)	(6.60)	(12.34)	(5.98)	(7.17)
	Seed maturity	25.45 b (a)	20.18 b (a)	23.17 b (a)	25.34 b (a)	21.75 b (a)	18.57 b (a)	12.8 b (a)	12.66 b (a)
		(4.08)	(2.75)	(9.95)	(6.64)	(5.30)	(2.94)	(4.02)	(3.43)

Table 10, Continued...

TLA (g cm^{-2})	First bloom	4.50 b (a)	3.27 b (a)	2.13 b (a)	1.70 b (a)	4.44 a (a)	4.18 b (a)	3.91 b (a)	4.02 b (a)
		(2.10)	(0.40)	(0.48)	(0.45)	(1.26)	(1.13)	(0.32)	(0.62)
	Seed maturity	9.97 a (a)	12.33 a (a)	14.07 a (a)	11.62 a (a)	11.04 a (b)	12.45 a (b)	22.54 a (a)	24.02 a (a)
		(2.44)	(0.91)	(5.35)	(4.65)	(2.40)	(2.55)	(6.80)	(7.68)

Table 11. Whole plant transpiration-use efficiency (TE) and whole plant water conversion (WC) of common lambsquarters as influenced by fraction of transpirable soil water level, time of harvest and experiment run. Means followed by different letters in parenthesis within a row for a given parameter are different at P<0.05.

Variable	Fraction of transpirable soil water				Harvest		Experimental run	
	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	First bloom (±SE)	Seed maturity (±SE)	1 (±SE)	2 (±SE)
TE ($g\ kg^{-1}$)	4.86 (a) (1.73)	4.63 (ab) (0.53)	4.06 (b) (0.59)	4.06 (b) (0.48)	4.84 (a) (1.21)	3.96 (b) (0.52)	4.22 (b) (0.59)	4.59 (a) (1.31)
WC ($g\ g^{-1}$)	218.64 (b) (40.66)	219.16 (b) (27.45)	251.52 (a) (38.52)	249.42 (a) (29.46)	212.55 (b) (27.03)	256.57 (a) (33.57)	242.04 (a) (36.86)	227.08 (b) (37.07)

Table 12. Biomass-above ground (Y_a) and total biomass (Y) of common lambsquarters as influenced by experimental run and fraction of transpirable soil water. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Experiment run	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y_a (g)	Run 1	0.473 a (b) (0.15)	2.204 a (b) (1.50)	7.694 b (a) (6.54)	6.963 b (a) (6.59)
	Run 2	1.48 a (c) (0.96)	2.967 a (c) (2.31)	11.443 a (b) (5.57)	15.317 a (a) (7.10)
Y (g)	Run 1	0.542 a (b) (0.16)	2.323 a (b) (1.52)	8.12 b (a) (6.97)	7.321 b (a) (6.96)
	Run 2	1.613 a (c) (1.06)	3.173 a (c) (2.49)	12.204 a (b) (5.86)	17.061 a (a) (8.26)

Table 13. Analysis of variance for pinnate tansymustard as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SKc), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	<0.0001	<0.0001	0.4228	0.7353	0.0016	0.0249	<0.0001	<0.0001	<0.0001	<0.0001	0.0302	<0.0001	0.8510
F	0.0193	0.0406	0.0464	0.0816	0.1743	0.6556	0.0004	<0.0001	<0.0001	<0.0001	<0.0001	0.4155	0.5726
H	0.0980	0.5613	0.0267	0.2734	<0.0001	0.0028	0.7758	<0.0001	<0.0001	<0.0001	0.8064	<0.0001	<0.0001
E X F	0.6513	0.6168	0.5379	0.5801	0.7708	0.8112	0.0178	0.0217	0.0147	0.0963	0.1495	0.0075	0.0826
E X H	0.2259	0.7006	0.7896	0.7193	0.0072	0.1259	0.0003	0.0074	0.0023	0.0229	<0.0001	<0.0001	<0.0001
F X H	0.7094	0.9527	0.4152	0.7387	0.0320	0.0448	0.1187	0.0005	0.0016	0.0004	0.7208	0.0801	0.3662
E X F X H	0.6432	0.7933	0.4416	0.5229	0.9658	0.8172	0.0398	0.3736	0.3553	0.8950	0.0496	0.3306	0.3605
Experimental run 1													
F							0.0051						
H							0.0576						
F X H							0.1484						
Experimental run 2													
F							0.0013						
H							<0.0001						
F X H							0.0055						

Table 14. Whole plant water conversion (WC), biomass-aboveground (Y_a), total biomass (Y) and cumulative transpiration (T) of pinnate tansymustard as influenced by fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
WC ($g\ g^{-1}$)	First bloom	329.46 b (a) (93.55)	335.11 b (a) (64.72)	449.43 a (a) (41.13)	410.42 a (a) (85.99)
	Seed maturity	487.96 a (a) (204.56)	485.49 a (a) (96.29)	452.58 a (a) (104.50)	507.80 a (a) (77.59)
Y_a (g)	First bloom	1.65 a (b) (1.17)	3.16 a (ab) (1.62)	3.95 b (ab) (2.07)	4.78 b (a) (2.13)
	Seed maturity	2.17 a (b) (1.37)	3.80 a (b) (2.33)	7.92 a (a) (4.00)	8.74 a (a) (3.03)
Y (g)	First bloom	1.97 a (b) (1.52)	4.13 a (ab) (2.11)	4.68 b (ab) (2.57)	5.64 b (a) (2.76)
	Seed maturity	2.45 a (b) (1.57)	4.39 a (b) (2.91)	9.00 a (a) (5.03)	9.56 a (a) (3.54)
T (g)	First bloom	641.68 a (b) (578.19)	1363.71 a (ab) (647.82)	2061.38 b (a) (985.21)	2227.53 b (a) (938.11)
	Seed maturity	1072.64 a (b) (678.71)	1917.82 a (b) (1014.82)	3699.02 a (a) (1609.96)	4689.05 a (a) (1527.02)

Table 15. Biomass-belowground (Y_b) of pinnate tansymustard as influenced by fraction of transpirable soil water, time of harvest, and experiment run. Means followed by different letters within a column for a run are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Experiment	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Run 1	First bloom	0.13 a (c) (0.05)	0.74 a (ab) (0.42)	0.36 a (bc) (0.19)	1.10 a (a) (0.70)
	Seed maturity	0.08 a (a) (0.05)	0.10 b (a) (0.03)	0.23 a (a) (0.31)	0.21 b (a) (0.08)
Run 2	First bloom	0.53 a (a) (0.47)	1.19 a (a) (0.60)	1.10 a (a) (0.58)	0.63 a (a) (0.64)
	Seed maturity	0.47 a (b) (0.16)	1.09 a (ab) (0.44)	1.93 (a) (a) (1.10)	1.42 a (ab) (0.79)

Table 16. Whole plant water conversion (WC), biomass-aboveground (Y_b), total biomass (Y), leaf area (LA), leaf area ratio (LAR) and transpiration per unit leaf area (TLA) of pinnate tansymustard as influenced by experiment run and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Experiment	Harvest	
		First bloom (±SE)	Seed maturity (±SE)
WC ($g\ g^{-1}$)	Run 1	375.94 a (a) (94.00)	422.15 b (a) (62.91)
	Run 2	386.28 a (b) (83.79)	544.76 a (a) (146.86)
Y_a (g)	Run 1	4.08 a (b) (2.05)	7.41 a (a) (3.56)
	Run 2	2.69 a (a) (1.92)	3.91 b (a) (3.51)
Y (g)	Run 1	4.94 a (b) (2.57)	8.63 a (a) (4.28)
	Run 2	3.27 a (a) (2.39)	4.06 b (a) (3.61)
T (g)	Run 1	1859.24 a (b) (984.91)	3557.39 a (a) (1682.76)
	Run 2	1287.81 a (b) (963.61)	2131.88 b (a) (1848.76)
LA (cm^2)	Run 1	225.03 a (b) (115.51)	321.80 a (a) (136.71)
	Run 2	276.93 a (a) (205.81)	168.90 b (b) (153.40)
LAR ($cm^2\ g^{-1}$)	Run 1	46.07 b (a) (3.45)	39.08 a (a) (7.26)
	Run 2	81.71 a (a) (16.13)	44.22 a (b) (20.16)
TLA ($g\ cm^{-2}$)	Run 1	8.21 a (b) (2.05)	11.06 b (a) (1.99)
	Run 2	4.74 b (b) (0.46)	14.27 a (a) (6.02)

Table 17. Biomass-aboveground (Y_a), total biomass (Y) and leaf area ratio (LAR) of pinnate tansymustard as influenced by experiment run and fraction of transpirable soil water. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Experiment	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y_a (g)	Run 1	2.89 a (c) (1.07)	5.04 a (bc) (1.60)	7.92 a (a) (3.98)	7.12 a (ab) (3.35)
	Run 2	0.93 a (c) (0.42)	1.92 b (bc) (0.66)	3.95 b (b) (2.12)	6.40 a (a) (3.28)
Y (g)	Run 1	3.39 a (c) (1.31)	6.18 a (bc) (1.98)	9.43 a (a) (4.71)	8.15 a (ab) (4.07)
	Run 2	1.03 a (c) (0.40)	2.34 b (bc) (0.99)	4.24 b (b) (2.27)	7.05 a (a) (3.36)
LAR (cm^2 g^{-1})	Run 1	43.94 a (a) (4.12)	41.84 b (a) (5.16)	38.26 b (a) (8.52)	46.24 a (a) (5.88)
	Run 2	55.07 a (b) (25.61)	63.80 a (ab) (26.19)	73.01 a (a) (25.31)	60.00 a (ab) (27.48)

Table 18. Whole plant transpiration-use efficiency (TE) of pinnate tansymustard as influenced by fraction of transpirable soil water, time of harvest and experiment run. Means followed by different lower case letters in parenthesis within a row are different at P<0.05.

Variable	Fraction of transpirable soil water				Harvest		Experiment run	
	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	First bloom (±SE)	Seed maturity (±SE)	1 (±SE)	2 (±SE)
TE ($g\ kg^{-1}$)	3.04 (a) (1.93)	2.60 (a) (0.65)	2.29 (a) (0.42)	2.27 (a) (0.47)	2.79 (a) (0.80)	2.30 (b) (1.29)	2.63 (a) (0.70)	2.46 (a) (1.39)

Table 19. Analysis of variance for dandelion as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	<0.0001	0.8514	0.0694	0.0041	0.0003	0.0354	0.3755	<0.0001	0.0006	<0.0001	<0.0001	<0.0001	0.0107
F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H	0.5262	0.0048	0.6153	0.0265	0.1259	0.0231	0.0010	0.7696	0.0175	0.3856	0.9328	0.0477	0.0069
E X F	0.0207	0.1981	0.0589	0.0596	<0.0001	0.0229	0.0611	0.0002	0.0456	0.1160	0.0006	0.0004	0.1214
E X H	0.5121	0.6155	0.9492	0.9157	0.8291	0.7393	0.6497	0.5232	0.5512	0.5526	0.4126	0.3743	0.7969
F X H	0.0024	0.2929	0.0230	0.7283	0.0585	0.3903	<0.0001	0.1346	0.0002	0.4631	0.1468	0.1899	0.3741
E X F X H	0.1072	0.8662	0.4884	0.7788	0.4805	0.9060	0.9108	0.1677	0.6978	0.3548	0.1754	0.7663	0.9505

Table 20. Whole plant transpiration-use efficiency (TE), biomass-belowground (Y_b) and total biomass (Y) of dandelion as influenced by fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	First bloom	1.78 a (b) (0.75)	2.61 a (ab) (0.64)	3.21 a (a) (1.00)	3.00 a (a) (0.87)
	Seed maturity	1.44 a (c) (0.56)	2.51 a (b) (0.61)	2.61 a (b) (0.71)	3.72 a (a) (1.00)
Y_b (g)	First bloom	0.49 a (c) (0.50)	2.20 a (bc) (1.22)	4.51 a (b) (2.95)	8.52 b (a) (3.93)
	Seed maturity	0.42 a (c) (0.27)	2.11 a (bc) (0.97)	5.02 a (b) (2.68)	15.70 a (a) (4.97)
Y (g)	First bloom	0.90 a (b) (0.79)	3.78 a (b) (1.99)	9.16 a (a) (6.79)	13.93 b (a) (6.24)
	Seed maturity	0.74 a (c) (0.40)	3.62 a (bc) (1.80)	8.74 a (b) (3.60)	22.65 a (a) (6.76)

Table 21. Whole plant transpiration-use efficiency coefficient (K_c), whole plant water conversion (WC), biomass-aboveground (Y_a), leaf area (LA) and leaf area ratio (LAR) of dandelion as influenced by of experiment run and fraction of transpirable soil water. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Experiment	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
K_c (Pa)	Run 1	3.80 a (b) (1.05)	4.84 a (b) (0.66)	4.64 a (b) (1.18)	6.81 a (a) (2.03)
	Run 2	1.87 b (b) (0.57)	3.61 a (a) (0.74)	4.33 a (a) (1.44)	4.65 b (a) (1.13)
WC ($g\ g^{-1}$)	Run 1	528.83 b (a) (159.52)	375.87 a (ab) (66.35)	393.90 a (ab) (126.97)	305.06 a (b) (80.29)
	Run 2	955.09 a (a) (366.28)	448.78 a (b) (111.20)	359.12 a (b) (115.20)	338.39 a (b) (99.40)
Y_a (g)	Run 1	0.35 a (b) (0.27)	0.83 a (b) (0.38)	2.27 b (ab) (0.72)	3.95 b (a) (1.16)
	Run 2	0.39 a (b) (0.27)	2.27 a (b) (0.62)	6.10 a (a) (3.69)	8.42 a (a) (3.46)
LA (cm^2)	Run 1	50.15 a (b) (42.41)	119.79 a (b) (57.87)	301.47 b (ab) (101.80)	577.05 b (a) (179.88)
	Run 2	59.40 a (c) (42.91)	329.94 a (c) (100.44)	800.42 a (b) (527.55)	1208.10 a (a) (524.22)
LAR ($cm^2\ g^{-1}$)	Run 1	51.43 b (ab) (6.35)	49.64 a (ab) (13.21)	60.80 a (a) (21.54)	37.82 b (b) (13.07)
	Run 2	90.03 a (a) (17.31)	66.83 a (b) (10.30)	62.34 a (b) (17.30)	62.65 a (b) (14.33)

Table 22. Cumulative transpiration (T) and transpiration per unit leaf area (TLA) of dandelion as influenced by experiment run, fraction of transpirable soil water and time of harvest. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Fraction of transpirable soil water				Harvest		Experiment	
	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	First bloom (±SE)	Seed maturity (±SE)	Run 1 (±SE)	Run 2 (±SE)
T (g)	515.07 (c)	1577.40 (c)	3400.29 (b)	5745.36 (a)	2654.51 (a)	2964.55 (a)	2061.61 (b)	3557.45 (a)
	(288.37)	(928.74)	(2403.92)	(2807.06)	(2760.67)	2742.13	(1875.53)	(3244.92)
TLA (g cm^{-2})	10.45 (a)	7.23 (b)	6.51 (b)	7.02 (b)	7.16 (b)	8.44 (a)	8.40 (a)	7.20 (b)
	(2.92)	(1.31)	(2.44)	(2.61)	(2.76)	(2.79)	(2.74)	(2.82)

Table 23. Analysis of variance for henbit as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC) biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	0.6499	0.0138	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0353	0.0093	<0.0001	<0.0001
F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.1197
H	0.0011	<0.0001	0.0499	0.0010	0.0083	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
E X F	0.7437	0.5903	0.0186	0.0012	<0.0001	<0.0001	0.0055	0.0089	0.0041	0.0170	0.0044	0.2929	<0.0001
E X H	0.1647	0.0093	0.9343	0.3350	0.3769	0.1421	0.1798	0.0013	0.0017	<0.0001	0.0253	<0.0001	0.0097
F X H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0104	0.0652
E X F X H	0.7773	0.8674	0.6333	0.3182	0.9914	0.6168	0.6864	<0.0001	<0.0001	<0.0001	0.0010	0.0003	0.0069
Experimental run 1													
F								<0.0001	<0.0001	<0.0001	<0.0001	0.0103	<0.0001
H								<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
F X H								<0.0001	<0.0001	<0.0001	<0.0001	0.0004	<0.0001
Experimental run 2													
F								<0.0001	<0.0001	<0.0001	<0.0001	0.0002	0.0077
H								0.0930	0.0468	0.0028	0.0974	0.0409	0.0079
F X H								0.5220	0.5011	0.0438	0.2170	0.0572	0.6835

Table 24. Biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA) of henbit as influenced by fraction of transpirable soil water, time of harvest and experiment run. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row for an experiment are different at P<0.05.

		Fraction of transpirable soil water							
Variable	Harvest	Run 1				Run 2			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y_a (g)	First bloom	0.23 a (a) (0.05)	0.21 a (a) (0.05)	0.14 a (a) (0.04)	0.38 b (a) (0.10)	0.31 a (b) (0.05)	0.26 a (b) (0.08)	0.62 a (b) (0.38)	1.42 a (a) (0.65)
	Seed maturity	0.26 a (b) (0.07)	0.20 a (b) (0.02)	0.43 a (b) (0.14)	2.08 a (a) (0.43)	0.34 a (c) (0.10)	0.31 a (c) (0.09)	1.01 a (ab) (0.31)	1.59 a (a) (0.37)
Y (g)	First bloom	0.26 a (a) (0.06)	0.23 a (a) (0.05)	0.17 a (a) (0.05)	0.43 b (a) (0.11)	0.36 a (b) (0.06)	0.32 a (b) (0.12)	0.79 a (b) (0.49)	1.72 a (a) (0.76)
	Seed maturity	0.31 a (b) (0.08)	0.24 a (b) (0.03)	0.53 a (b) (0.16)	2.45 a (a) (0.55)	0.40 a (c) (0.10)	0.39 a (c) (0.10)	1.20 a (b) (0.34)	2.07 a (a) (0.31)
T (g)	First bloom	77.21 a (a) (7.49)	76.01 a (a) (19.72)	64.40 b (a) (32.26)	175.64 b (a) (47.36)	108.24 a (b) (12.76)	88.45 a (b) (23.73)	210.30 a (b) (138.73)	523.02 a (a) (196.38)
	Seed maturity	86.03 a (c) (20.16)	81.16 a (c) (7.92)	246.11 a (b) (84.26)	1117.94 a (a) (206.91)	102.91 a (c) (29.19)	107.53 a (c) (27.43)	401.20 a (b) (127.51)	722.47 a (a) (142.92)
LA (cm^2)	First bloom	37.71 a (b) (6.78)	30.28 a (b) (9.17)	22.05 b (b) (8.95)	78.26 b (a) (20.33)	31.18 a (b) (10.39)	21.03 a (b) (7.64)	58.82 a (b) (36.48)	157.72 a (a) (56.35)
	Seed maturity	29.02 a (b) (8.90)	25.57 a (b) (2.07)	50.26 a (b) (13.20)	221.03 a (a) (30.81)	23.13 a (c) (9.47)	21.36 a (c) (6.25)	90.19 a (b) (23.04)	199.36 a (a) (59.52)
LAR (cm^2 g^{-1})	First bloom	134.60 a (b) (25.97)	129.69 a (b) (13.02)	129.16 a (b) (20.39)	183.89 a (a) (30.19)	87.00 a (a) (25.80)	67.27 a (a) (23.82)	73.67 a (a) (6.98)	94.33 a (a) (16.31)
	Seed maturity	94.69 b (a) (23.93)	107.58 a (a) (9.96)	96.05 a (a) (9.13)	92.32 b (a) (11.42)	55.29 b (b) (15.05)	55.61 a (b) (7.72)	76.31 a (ab) (9.81)	96.74 a (a) (15.93)
TLA (g cm^{-2})	First bloom	2.36 a (a) (0.44)	2.55 a (a) (0.19)	2.90 b (a) (0.53)	2.30 b (a) (0.51)	3.71 a (a) (1.02)	4.61 a (a) (1.49)	3.54 a (a) (0.44)	3.35 a (a) (0.51)
	Seed maturity	3.06 a (b) (0.58)	3.18 a (b) (0.19)	4.78 a (a) (0.62)	5.04 a (a) (0.49)	4.83 a (a) (1.23)	5.08 a (a) (0.53)	4.47 a (a) (0.83)	3.71 a (a) (0.38)

Table 25. Whole plant transpiration-use efficiency (TE), whole plant water conversion (WC) and biomass-belowground (Y_b) of henbit as influenced by fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	First bloom	3.33 a (ab) (0.53)	3.36 a (a) (0.65)	3.33 a (ab) (0.71)	2.85 a (b) (0.45)
	Seed maturity	3.79 a (a) (0.35)	3.28 a (b) (0.46)	2.62 b (c) (0.55)	2.53 a (c) (0.40)
WC (g g^{-1})	First bloom	307.08 a (b) (46.01)	306.33 a (b) (47.95)	315.75 b (ab) (80.71)	359.92 a (a) (59.39)
	Seed maturity	266.19 a (b) (27.73)	310.67 a (b) (43.38)	396.73 a (a) (76.92)	403.67 a (a) (63.64)
Y_b (g)	First bloom	0.04 a (b) (0.02)	0.04 a (b) (0.04)	0.10 a (ab) (0.11)	0.17 b (a) (0.15)
	Seed maturity	0.05 a (b) (0.01)	0.06 a (b) (0.02)	0.14 a (b) (0.06)	0.42 a (a) (0.21)

Table 26. Whole plant transpiration-use efficiency (TE), whole plant water conversion (WC) and biomass-belowground (Y_b) of henbit as influenced by experiment run and fraction of transpirable soil water. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Experiment	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	Run 1	3.44 a (a) (0.45)	3.00 b (a) (0.22)	2.49 b (b) (0.48)	2.32 b (b) (0.23)
	Run 2	3.68 a (a) (0.54)	3.63 a (a) (0.61)	3.45 a (ab) (0.59)	3.07 a (b) (0.25)
WC (g g^{-1})	Run 1	295.58 a (b) (40.56)	334.69 a (b) (24.73)	414.59 a (a) (76.05)	435.43 a (a) (40.92)
	Run 2	277.69 a (a) (44.48)	282.31 b (a) (45.64)	297.90 b (a) (52.89)	328.15 b (a) (25.88)
Y_b (g)	Run 1	0.04 a (b) (0.02)	0.03 a (b) (0.02)	0.06 b (b) (0.04)	0.21 b (a) (0.19)
	Run 2	0.06 a (c) (0.02)	0.07 a (c) (0.04)	0.18 a (b) (0.09)	0.39 a (a) (0.21)

Table 27. Analysis of variance for shepherd's-purse as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.6732	0.6154	0.7232	0.0215	0.0030	<0.0001	0.9729
F	0.7466	0.1206	0.6803	0.0439	0.0758	0.0101	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0462	<0.0001	<0.0001
E X F	0.9883	0.4598	0.9977	0.6917	0.9782	0.9520	0.3948	0.1465	0.1494	0.0881	0.0308	0.0013	0.9999
E X H	0.5489	0.8827	0.2832	0.5765	0.3277	0.3475	0.8848	0.9445	0.9307	0.4573	0.4732	0.0601	0.9730
F X H	0.0031	0.0004	0.0015	0.0002	<0.0001	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	0.2431	<0.0001	0.0003
E X F X H	0.9224	0.7966	0.9865	0.7331	0.1125	0.0650	0.2734	0.0879	0.0898	0.2590	0.3736	<0.0001	0.9999
Experimental run 1													
F												0.0011	
H												<0.0001	
F X H												0.0001	
Experimental run 2													
F												<0.0001	
H												<0.0001	
F X H												<0.0001	

Table 28. Whole plant transpiration-use efficiency (TE), whole plant water conversion (WC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T) and transpiration per unit leaf area (TLA) of shepherd's-purse as influenced by fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	First bloom	2.91 a (a) (1.43)	3.20 a (a) (0.59)	2.55 a (a) (0.51)	2.50 a (a) (0.47)
	Seed maturity	1.90 b (a) (0.41)	2.00 b (a) (0.66)	2.30 a (a) (0.46)	2.57 a (a) (0.55)
WC (g g^{-1})	First bloom	395.06 b (a) (126.81)	322.06 b (a) (56.74)	406.01 a (a) (80.95)	413.94 a (a) (77.54)
	Seed maturity	556.46 a (a) (158.39)	539.48 a (a) (140.70)	449.41 a (ab) (76.74)	405.36 a (b) (88.95)
Y_b (g)	First bloom	0.22 a (a) (0.20)	0.18 a (a) (0.11)	0.32 b (a) (0.11)	0.40 b (a) (0.16)
	Seed maturity	0.24 a (c) (0.13)	0.33 a (c) (0.11)	0.86 a (b) (0.38)	1.46 a (a) (0.49)
Y_a (g)	First bloom	0.65 a (a) (0.29)	0.86 a (a) (0.55)	1.44 b (a) (0.42)	2.10 b (a) (0.82)
	Seed maturity	1.26 a (c) (0.67)	2.08 a (c) (0.54)	6.25 a (b) (2.28)	8.30 a (a) (2.06)
Y (g)	First bloom	0.87 a (a) (0.40)	1.04 a (a) (0.65)	1.77 b (a) (0.52)	2.50 b (a) (0.97)
	Seed maturity	1.50 a (c) (0.79)	2.41 a (c) (0.60)	7.11 a (b) (2.56)	9.77 a (a) (2.45)
T (g)	First bloom	345.76 a (a) (215.05)	329.91 b (a) (209.87)	715.94 b (a) (250.88)	1048.87 b (a) (524.76)
	Seed maturity	788.83 a (b) (440.35)	1283.76 a (b) (420.45)	3136.14 a (a) (1263.68)	3954.64 a (a) (1275.38)
TLA (g cm^{-2})	First bloom	9.18 a (a) (4.47)	2.83 b (b) (0.33)	2.34 b (b) (0.32)	2.52 b (b) (0.09)
	Seed maturity	10.25 a (a) (0.80)	7.87 a (a) (1.23)	10.75 a (a) (2.65)	7.52 a (a) (1.08)

Table 29. Leaf area ratio (LAR) of shepherd's-purse as influenced by fraction of transpirable soil water, time of harvest and experiment run. Means followed by different letters within a column are different at P<0.05. Means followed by different letters in parenthesis within a row for an experiment are different at P<0.05.

Variable	Harvest	Fraction of transpirable soil water: Experiment run 1				Experiment run 2			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
LAR (cm^2 g^{-1})	First bloom	67.94 a (c)	95.65 a (bc)	148.28 a (a)	138.79 a (ab)	34.35 b (c)	136.25 a (b)	203.44 a (a)	190.02 a (a)
		(49.67)	(21.31)	(27.86)	(20.80)	(2.55)	(8.78)	(18.83)	(16.18)
	Seed maturity	44.96 a (a)	61.36 a (a)	38.82 b (a)	48.82 b (a)	64.09 a (ab)	76.13 b (a)	47.17 b (b)	59.86 b (ab)
		(5.49)	(13.59)	(8.10)	(10.79)	(17.01)	(16.30)	(3.16)	(10.52)

Table 30. Leaf area (LA) of shepherd's-purse as influenced by experiment run and fraction of transpirable soil water. Means followed by different letters within a column are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Experiment	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
LA (cm^2)	Run 1	56.48 a (c) (30.54)	128.41 a (bc) (64.79)	273.83 a (ab) (74.30)	382.87 b (a) (116.44)
	Run 2	60.39 a (c) (49.20)	154.81 a (c) (72.87)	334.52 a (b) (131.60)	560.35 a (a) (213.39)

Table 31. Analysis of variance for Carolina foxtail as influenced by experimental run (E), fraction of transpirable soil water (F) and time of harvest (H) for whole plant transpiration-use efficiency coefficient (K_c), shoot transpiration-use efficiency coefficient (SK_c), whole plant transpiration-use efficiency (TE), shoot transpiration-use efficiency (STE), whole plant water conversion (WC), shoot water conversion (SWC), biomass-belowground (Y_b), biomass-aboveground (Y_a), total biomass (Y), cumulative transpiration (T), leaf area (LA), leaf area ratio (LAR), and transpiration per unit leaf area (TLA).

	Response variable (Pr>F)												
	K_c	SK_c	TE	STE	WC	SWC	Y_b	Y_a	Y	T	LA	LAR	TLA
Pooled Data													
E	0.0245	<0.0001	0.5900	0.0006	0.0124	0.1442	<0.0001	0.0468	0.3031	0.0242	0.0273	<0.0001	0.6587
F	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0005	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
E X F	0.7204	0.0236	0.0973	0.3380	0.0181	0.0032	0.0006	0.0008	0.0421	0.0607	0.0005	0.4387	0.0910
E X H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0032	0.2243	0.0009	0.0090	0.8500	0.0006	0.1671	0.0003
F X H	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	0.0064	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
E X F X H	0.0005	0.3145	<0.0001	0.1785	0.0066	0.0182	0.7713	0.0422	0.1701	0.0030	0.0373	0.2067	0.3470
Experimental run 1													
F	<0.0001		<0.0001		<0.0001	<0.0009		<0.0001		<0.0001	<0.0001		
H	0.8403		0.9325		<0.0001	<0.0001		<0.0001		<0.0001	<0.0001		
F X H	<0.0001		<0.0001		<0.0001	<0.0001		0.0001		<0.0001	<0.0001		
Experimental run 2													
F	<0.0001		<0.0001		<0.0001	<0.0001		<0.0001		<0.0001	<0.0001		
H	<0.0001		<0.0001		<0.0001	<0.0001		<0.0001		<0.0001	<0.0001		
F X H	<0.0001		<0.0001		<0.0001	<0.0001		<0.0001		<0.0001	<0.0001		

Table 32. Whole plant transpiration-use efficiency (TE), whole plant water conversion (WC), biomass-aboveground (Y_a), cumulative transpiration (T), and leaf area (LA) of Carolina foxtail as influenced by fraction of transpirable soil water, time of harvest and experiment run. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row for an experiment are different at P<0.05.

		Fraction of transpirable soil water							
Variable	Harvest	Experimental run 1				Experimental run 2			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
TE (g kg^{-1})	First bloom	0.52 b (c)	1.59 a (b)	3.53 a (a)	4.40 a (a)	0.40 b (c)	1.33 b (b)	3.50 a (a)	2.82 a (a)
		(0.04)	(0.09)	(0.50)	(0.65)	(0.11)	(0.49)	(0.60)	(0.45)
	Seed maturity	2.01 a (b)	2.28 a (ab)	3.39 a (a)	2.32 b (ab)	2.43 a (b)	2.76 a (ab)	3.38 a (a)	3.07 a (ab)
		(0.09)	(0.13)	(0.88)	(0.25)	(0.24)	(0.33)	(0.11)	(0.47)
WC (g g^{-1})	First bloom	1915.11 a (a)	629.76 a (b)	287.42 a (c)	230.94 b (c)	2672.12 a (a)	873.97 a (b)	293.43 a (c)	360.88 a (bc)
		(139.40)	(34.61)	(35.91)	(34.05)	(642.93)	(431.03)	(53.70)	(50.63)
	Seed maturity	498.99 b (a)	439.54 b (a)	312.15 a (b)	434.42 a (ab)	414.59 b (a)	366.72 a (a)	296.12 a (a)	332.07 a (a)
		(22.70)	(24.44)	(81.36)	(44.14)	(40.63)	(41.16)	(9.37)	(54.25)
Y_a (g)	First bloom	0.09 a (b)	0.37 a (b)	3.54 a (a)	2.22 b (a)	0.05 a (b)	0.24 a (b)	2.25 b (a)	2.84 b (a)
		(0.01)	(0.06)	(0.73)	(0.74)	(0.02)	(0.14)	(0.85)	(0.82)
	Seed maturity	0.90 a (c)	1.10 a (c)	3.87 a (b)	5.28 a (a)	1.02 a (c)	1.18 a (c)	4.70 a (b)	7.44 a (a)
		(0.13)	(0.07)	(1.25)	(0.89)	(0.49)	(0.53)	(0.87)	(1.33)
T (g)	First bloom	206.83 a (b)	289.65 a (b)	1786.38 a (a)	997.94 b (a)	152.03 a (b)	208.48 a (b)	924.99 b (a)	1397.12 b (a)
		(28.32)	(45.84)	(619.24)	(501.63)	(24.27)	(56.82)	(199.99)	(291.98)
	Seed maturity	550.43 a (c)	550.71 a (c)	2009.76 a (b)	3741.50 a (a)	500.84 a (c)	497.60 a (c)	1871.01 a (b)	3277.07 a (a)
		(86.41)	(49.42)	(634.45)	(538.30)	(179.42)	(234.29)	(360.20)	(491.27)

Table 32, Continued…

LA (cm^2)	First bloom	11.00 a (c)	30.36 a (c)	280.43 a (b)	164.89 b (a)	6.89 a (b)	20.91 a (b)	180.34 b (a)	218.31 b (a)
		(1.60)	(4.65)	(57.22)	(56.78)	(2.02)	(10.73)	(66.73)	(56.33)
	Seed maturity	75.46 a (c)	90.06 a (c)	307.42 a (b)	418.17 a (a)	85.96 a (c)	99.29 a (c)	376.70 a (b)	591.90 a (a)
		(11.37)	(5.18)	(99.34)	(70.14)	(41.28)	(43.09)	(67.17)	(100.03)

Table 33. Total biomass (Y), leaf area ratio (LAR) and transpiration per unit leaf area (TLA) of Carolina foxtail as influenced by fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at P<0.05. Means followed by different letters in parenthesis within a row are different at P<0.05.

Variable	Harvest	Fraction of transpirable soil water			
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)
Y (g)	First bloom	0.08 a (b) (0.03)	0.38 a (b) (0.15)	4.72 a (a) (1.99)	4.19 b (a) (1.84)
	Seed maturity	1.17 a (c) (0.40)	1.30 a (c) (0.42)	6.40 a (b) (1.38)	9.37 a (a) (1.97)
LAR (cm^2 g^{-1})	First bloom	109.56 a (a) (18.39)	70.59 a (b) (7.42)	50.12 a (c) (5.75)	49.93 a (c) (10.43)
	Seed maturity	68.73 b (a) (2.64)	72.97 a (a) (2.52)	53.42 a (b) (7.62)	53.86 a (b) (7.20)
TLA (g cm^{-2})	First bloom	21.09 a (a) (4.79)	10.47 a (b) (3.33)	5.88 a (c) (1.23)	6.23 a (c) (1.06)
	Seed maturity	6.66 b (a) (0.88)	5.54 b (a) (0.77)	5.83 a (a) (1.62)	7.31 a (a) (2.06)

Table 34. Biomass-belowground (Y_b), total biomass (Y), and transpiration per unit leaf area (TLA) of Carolina foxtail as influenced by experiment run, fraction of transpirable soil water and time of harvest. Means followed by different letters within a column for a variable are different at $P<0.05$. Means followed by different letters in parenthesis within a row are different at $P<0.05$.

Variable	Experiment	Fraction of transpirable soil water				Harvest	
		0.3 (±SE)	0.4 (±SE)	0.7 (±SE)	1.0 (±SE)	First bloom (±SE)	Seed maturity (±SE)
Y_b (g)	Run 1	0.11 a (b) (0.09)	0.12 a (b) (0.03)	2.59 a (a) (0.72)	2.35 a (a) (1.36)	1.26 a (a) (1.55)	1.57 a(a) (1.48)
	Run 2	0.12 a (b) (0.12)	0.11 a (b) (0.09)	1.36 b (a) (0.52)	1.89 b (a) (1.18)	0.56 b (a) (0.58)	1.18 b (a) (1.23)
Y (g)	Run 1	0.61 a (b) (0.53)	0.86 a (b) (0.42)	6.29 a (a) (1.52)	6.60 a (a) (2.77)	2.66 a (b) (3.62)	4.36 a (a) (3.45)
	Run 2	0.65 a (c) (0.73)	0.82 a (c) (0.70)	4.83 a (b) (1.98)	7.03 a (a) (3.70)	1.90 b (b) (1.92)	4.76 a (a) (4.03)
TLA (g cm^{-2})	Run 1	13.15 a (a) (6.40)	7.83 a (b) (1.90)	6.47 a (b) (1.53)	7.42 a (b) (2.05)	10.54 a (a) (5.73)	7.29 a (b) (1.60)
	Run 2	14.60 a (a) (9.70)	8.18 a (b) (4.62)	5.24 a (c) (0.99)	6.04 a (bc) (0.93)	11.66 a (a) (7.98)	5.38 b (b) (0.69)

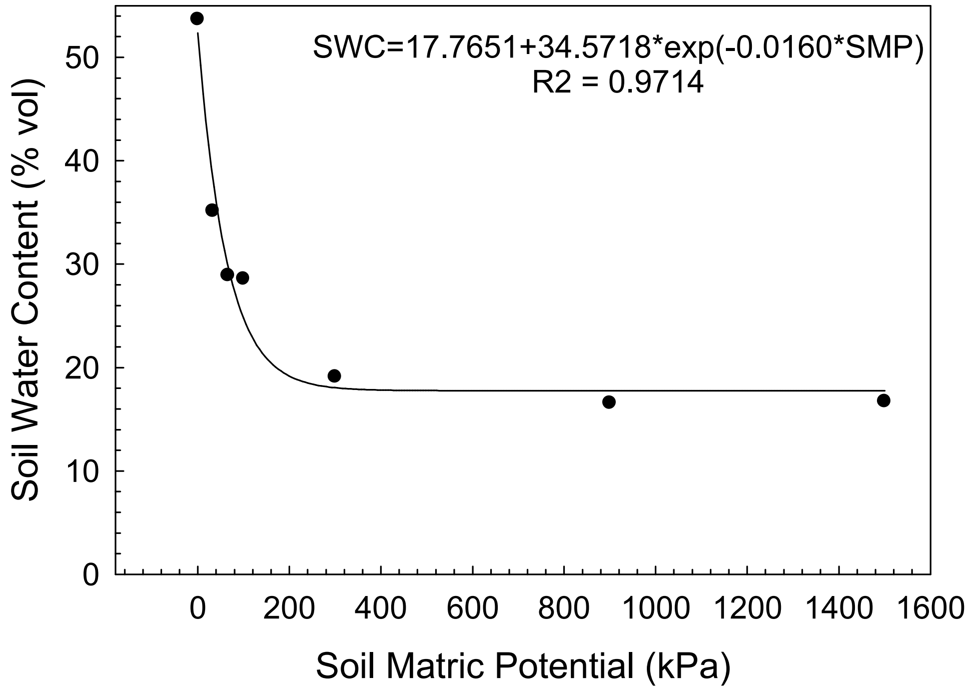


Figure 1. Soil water retention curve developed for greenhouse potting mixture.

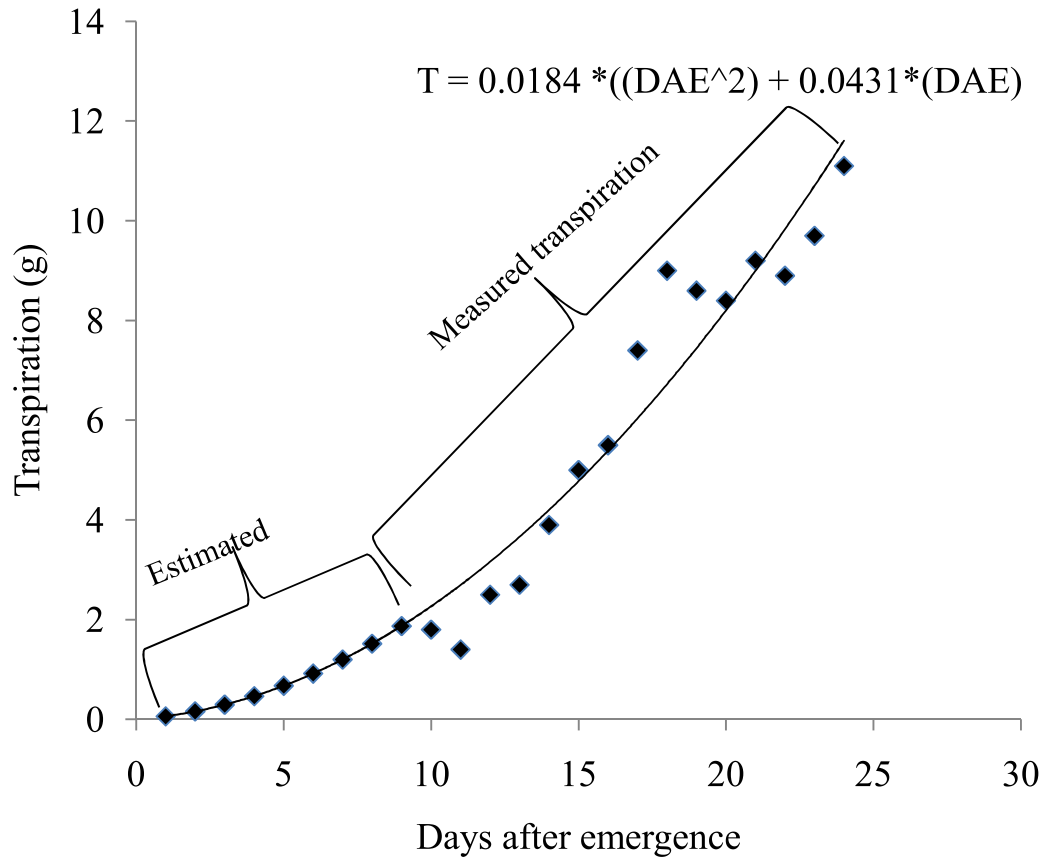
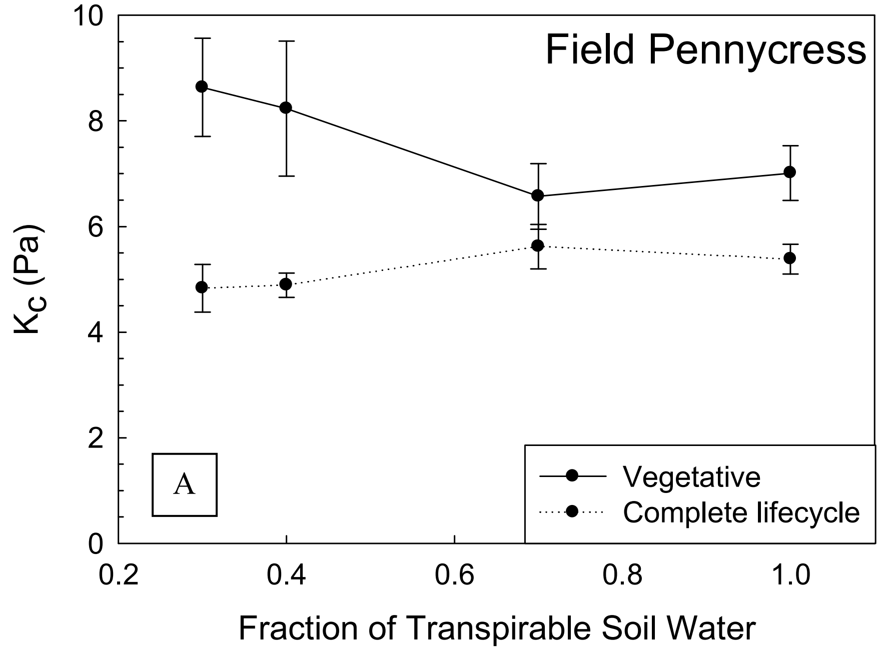


Figure 2. Daily transpiration prior to bagging was calculated by fitting a polynomial function to the measured daily transpiration during the first 20 days after bagging the plants, and forcing the function to pass through the origin. The figure represents the transpiration for one individual. Unique functions were calculated for each individual plant.



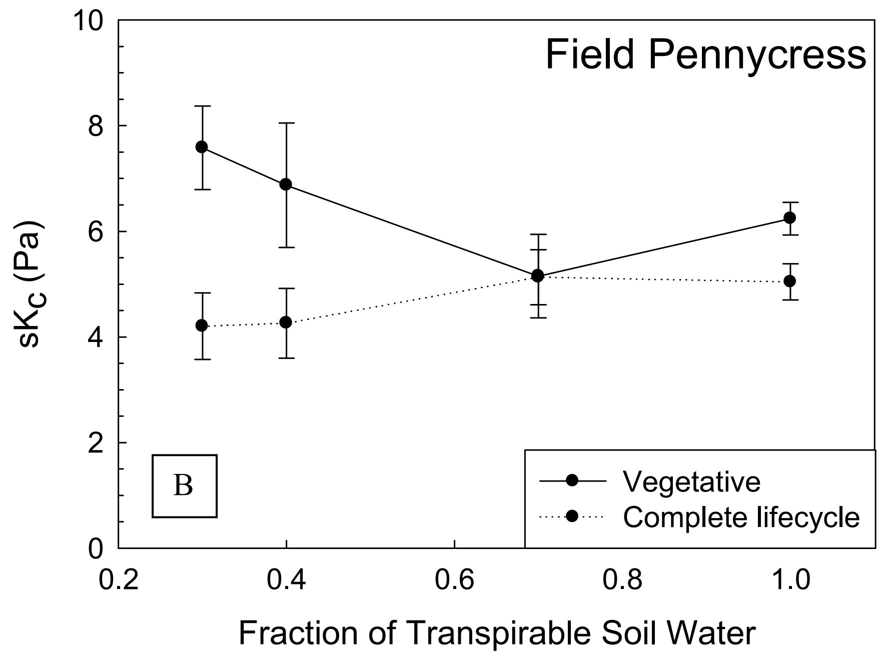
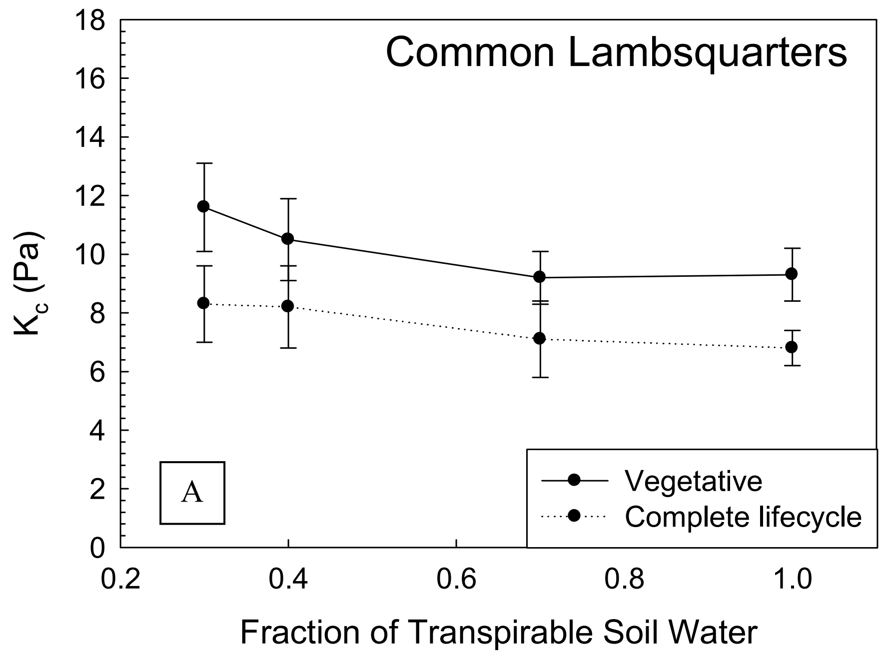


Figure 3. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (B) of field pennycress as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05



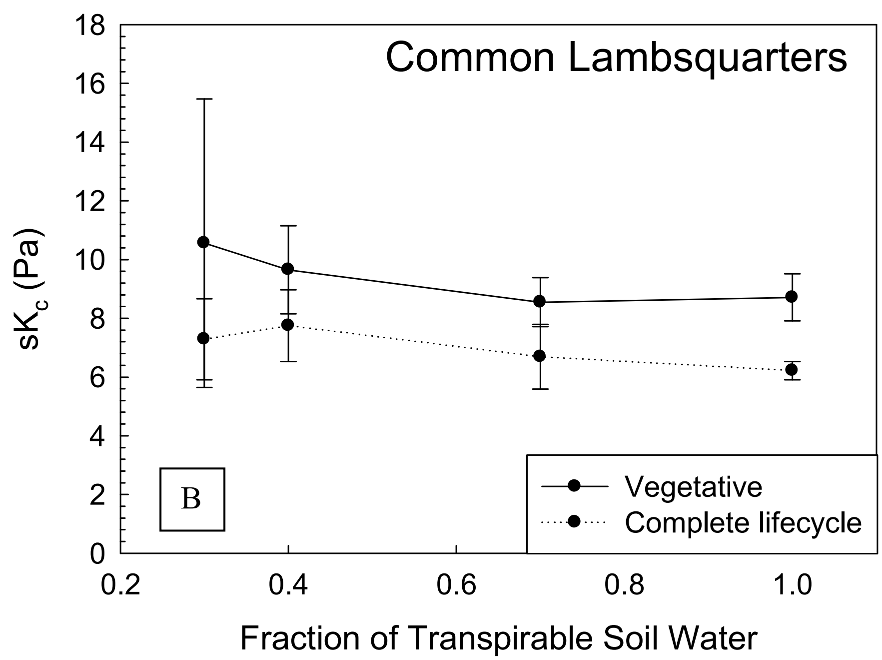


Figure 4. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (B) of common lambsquarters as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05

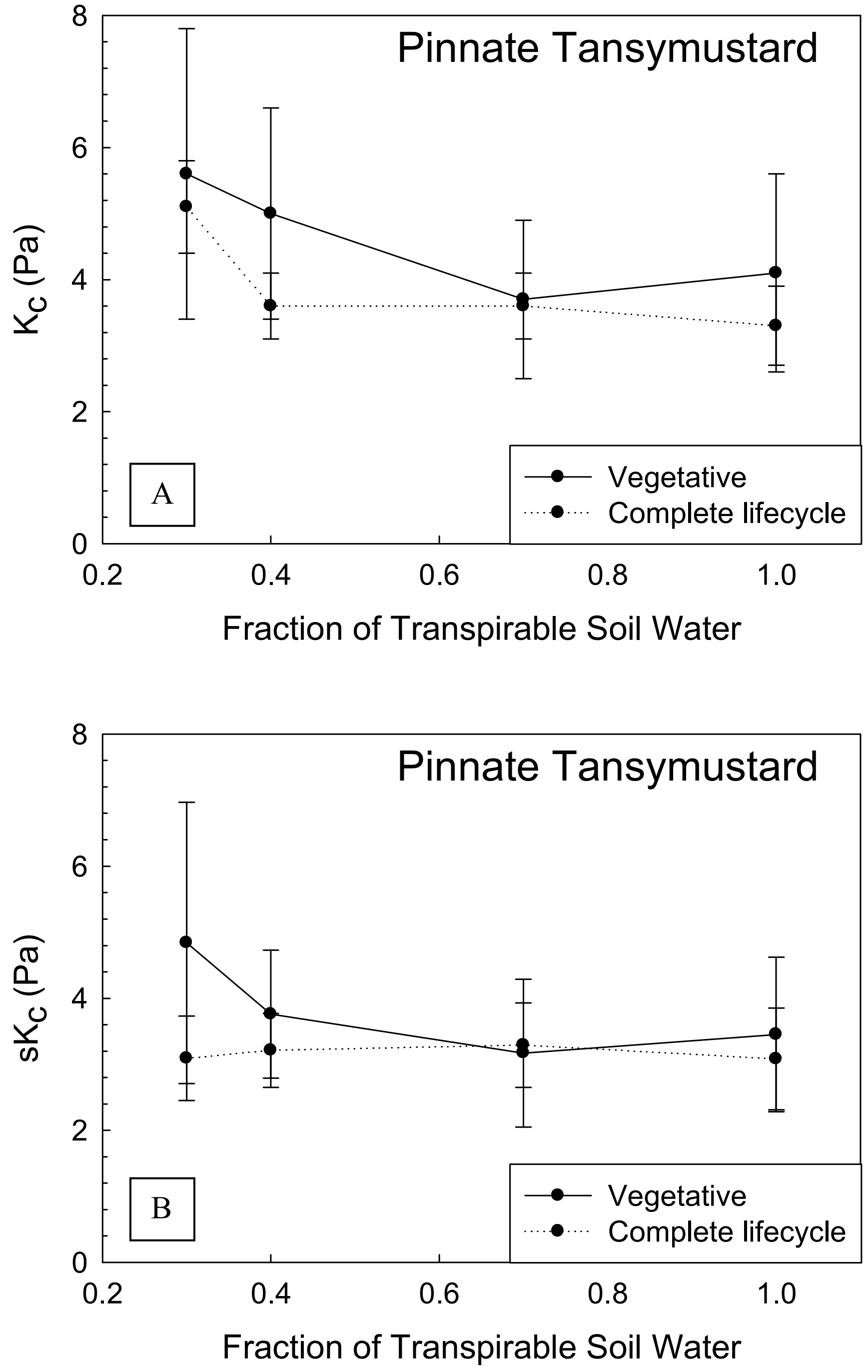


Figure 5. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (B) of pinnate tansymustard as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05

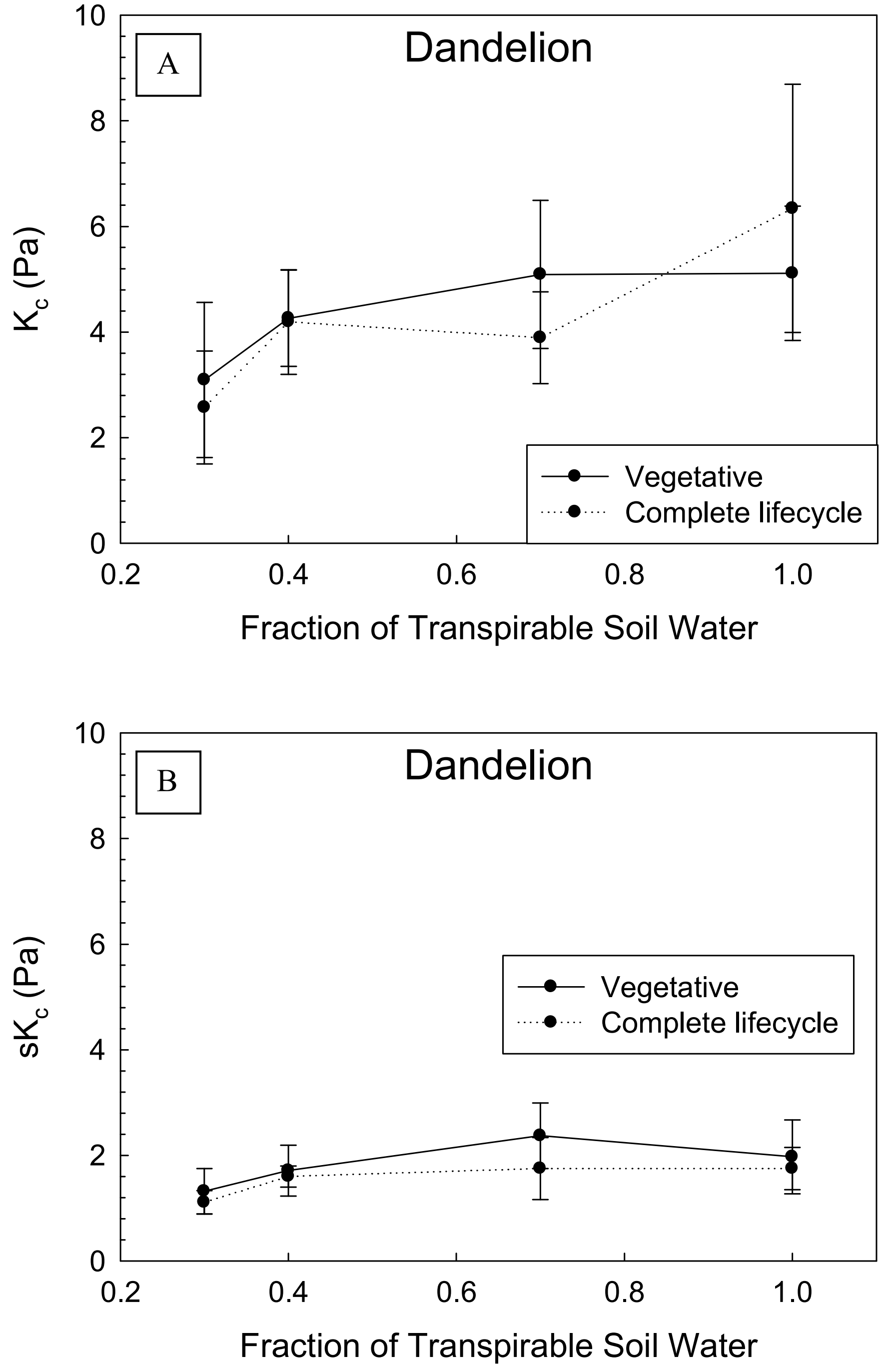
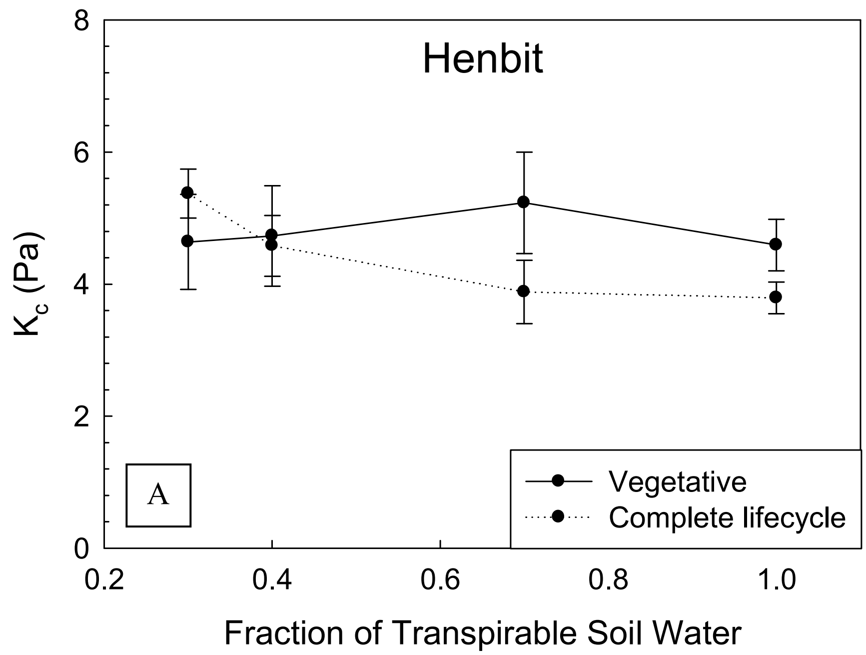


Figure 6. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (B) of dandelion as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05



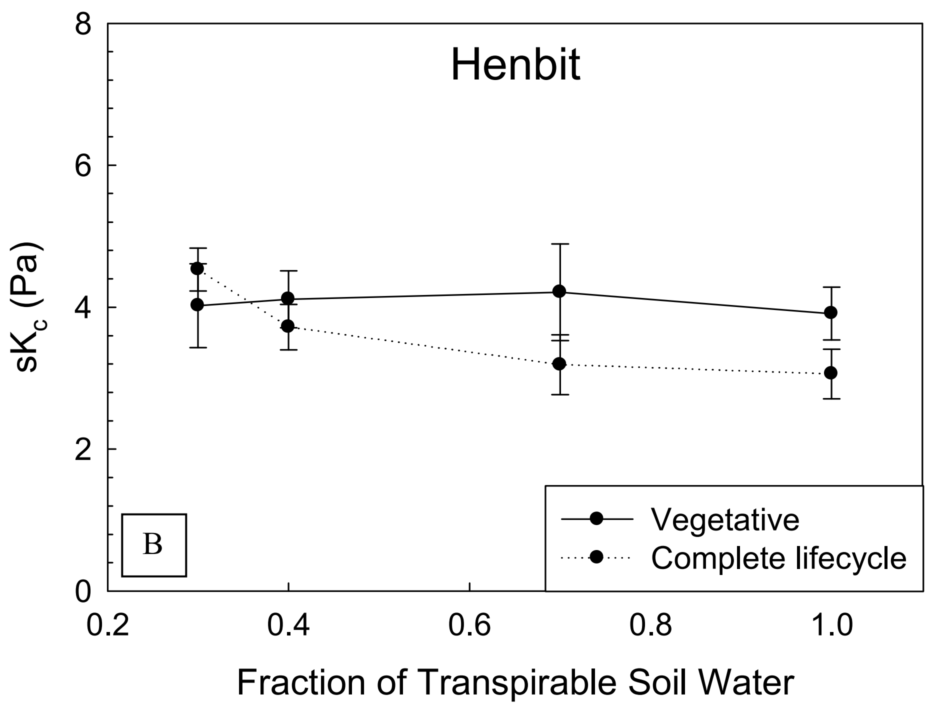


Figure 7. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (7B) of henbit as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05

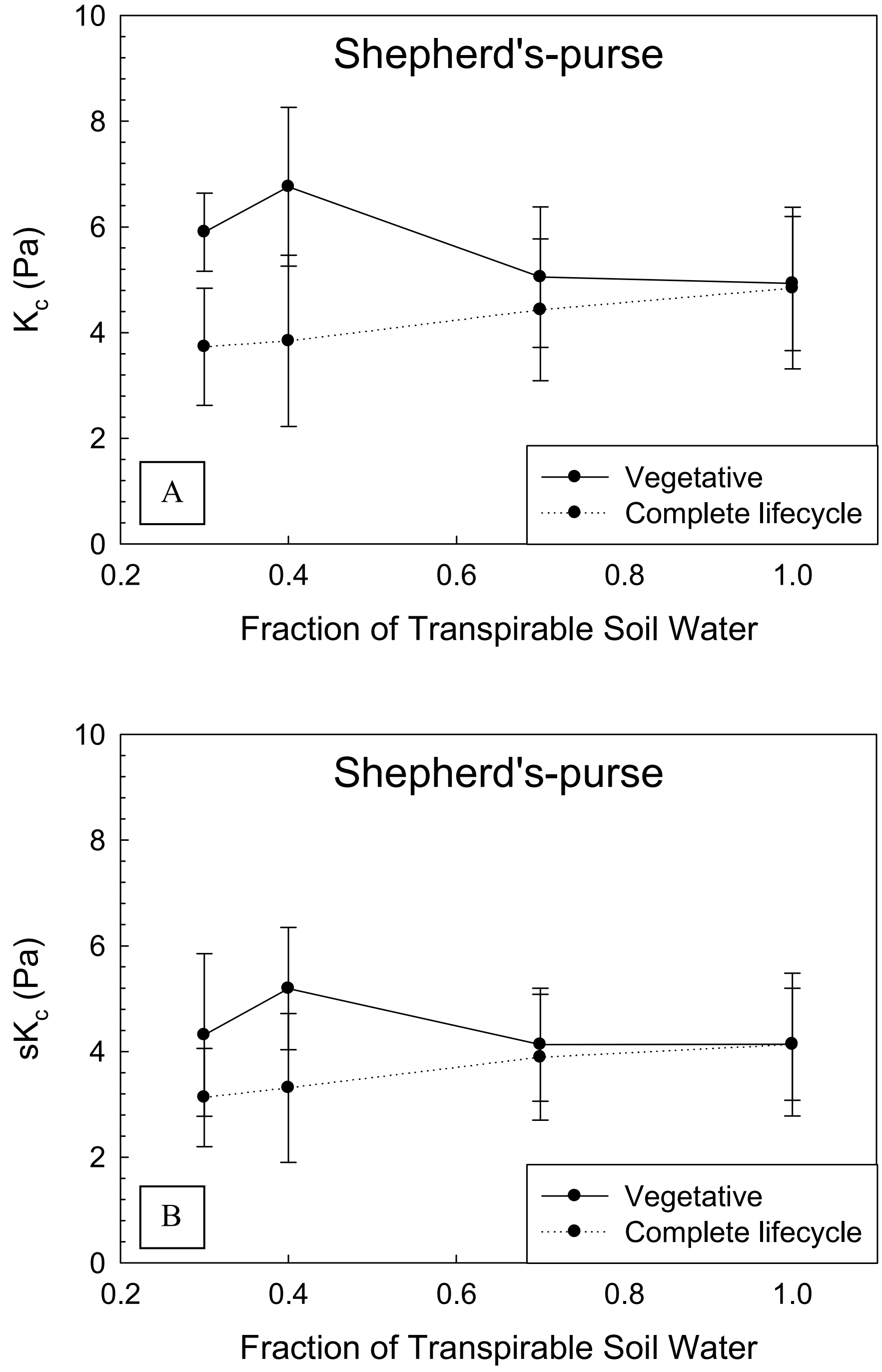


Figure 8. Whole plant transpiration-use efficiency coefficient (A) and shoot transpiration-use efficiency coefficient (B) of shepherd's-purse as influenced by fraction of transpirable soil water and time of harvest. Error bars represent standard errors at p=0.05

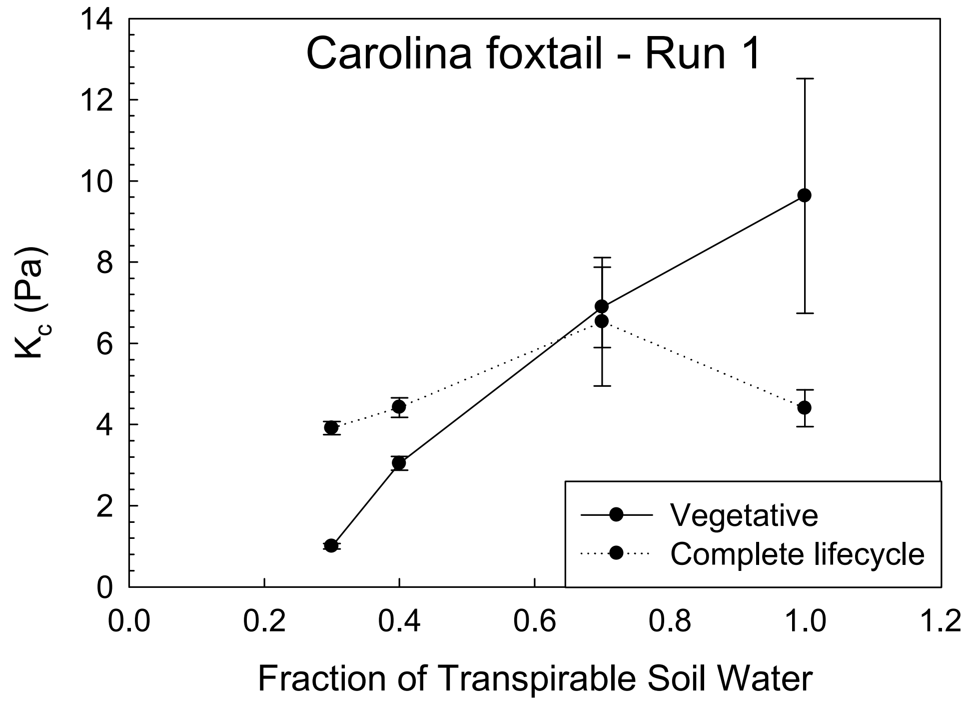


Figure 9. Whole plant transpiration-use efficiency coefficient of Carolina foxtail as influenced by fraction of transpirable soil water and time of harvest during experiment run 1.

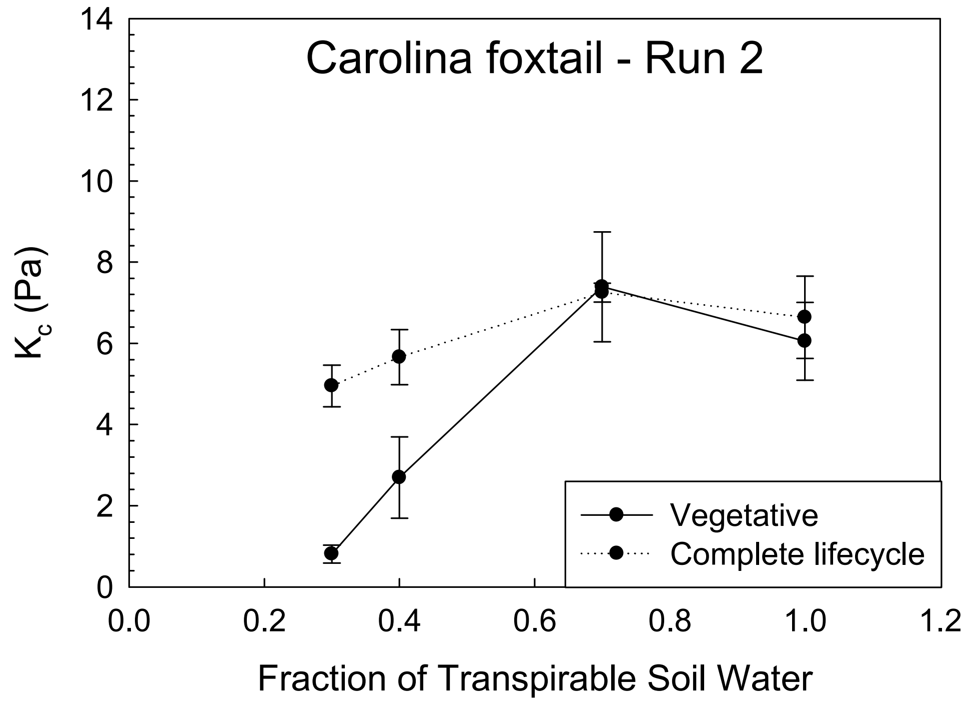


Figure 10. Whole plant transpiration-use efficiency coefficient of Carolina foxtail as influenced by fraction of transpirable soil water and time of harvest during experiment run 2.

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